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AIR FLOW MEASUREMENTS

By

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IPA Fellow

NATIONAL ENFORCEMENT INVESTIGATIONS CENTER

DENVER, COLORADO

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SYMBOLS

A	Cross-sectional area
a	Ambient. Actual.
C	Discharge coefficient. Specific Heat. Degrees Celcius. Correction factor.
c	Velocity of light. Corrected. Calibration condition.
D	Diameter
E	Energy. Compressibility Factor.
f	Measurement made in field. Rotameter float.
G	Gravity
g	Gas
H	Heat loss.
ΔH	Rotameter float height. Manometer liquid height.
h	Gas or liquid height.
K	Degrees Kelvine. Collection of critical flow constants.
k	Thermal conductivity.
L	Length
ℓ	Liquid
m	Pipe to orifice diameter ratio (D_p/D_o). Meter.
N	Avogadro's number.
n	Number of moles.
MW	Molecular weight.
o	Orifice. Observed.
P	Pressure
P_b	Barometric pressure
P_a	Ambient or actual pressure. Upstream pressure.
PPM	Parts per million (generally by volume in air data).
Q	Volumetric flowrate.
R	Gas constant. Degrees Rankine
r	Radius.
RH	Relative humidity.
STP	Standard temperature and pressure (0°C, 760 mm).

SYMBOLS (Continued)

Std	Standard conditions other than STP. (25°C, 760 mm; 70°F, 29.92 in Hg, etc.)
T	Temperature (°K; °R).
t	Temperature (°C; °F). Time.
V	Volume.
V _{bo}	Exterior spirometer volume.
V _{mt}	Metal Volume.
V _e	Displaced liquid volume.
v	Velocity.
w	Weight. Water.
α	Orifice coefficient of discharge.
γ	Ratio specific heat at constant pressure to specific heat at constant volume (C_p/C_v).
θ	Number of degrees above gas temperature.
λ	Wavelength.
μ	Viscosity. Micro.
ν	Frequency of radiant energy.
ρ	Density.
ϕ	Ratio of upstream to downstream pressures (P_1/P_2).

I. INTRODUCTION

Air flow measurement constitutes an essential step in the process of moving controlled streams of air for quantitative evaluation of their physical or chemical properties. In this report, the emphasis has been placed on those types of air flow measurements commonly encountered in the field of air pollution control.

Such measurements involve a wide range of devices employing principles of volumetric displacement, velocity impaction, viscosity, pressure, thermal conductivity, etc. The choice of a particular device or technique depends on a number of engineering as well as economic factors. In addition to the prime requirement that a device or technique must be able to make the desired measurement, other important considerations include accuracy, precision or repeatability, dependability in both field and laboratory operations, length of time and history of successful use, installation, calibration and maintenance costs.

Some devices can measure the volume or flowrate of a gas with a high degree of accuracy and dependability. They are consequently classified as primary standards. The primary standards can be used to calibrate the velocity or volumetric flowrate responses of intermediate and secondary standards. Any or all of these can subsequently be used directly or indirectly to measure the air streams being processed in the field or laboratory.

To use air flow measurement devices intelligently, their mechanical and theoretical operational principles should be understood at least on a qualitative basis. Changes in the gas composition, relative humidity, velocity and pressure have different effects on different

devices. For these purposes, this report discusses in a condensed manner the basic operational and theoretical principles of the more commonly used air pollution air flow measurement instruments.

The instruments are described briefly with respect to their mechanical use and operation. Simplified drawings of each representative type are shown. In each case the basic theoretical factors are illustrated through the presentation of a generalized mathematical equation which quantitatively indicates the role of such factors as pressure, temperature, viscosity, density, and specific heat. Additionally, in each case condensed mathematical equations are given for calculating volumetric flowrates when the temperature and pressure of the ambient or actual air significantly ($>4\%$) differ from the temperature and air pressure at the time of calibration.

In air pollution measurements, it is generally correct to assume that the composition of ambient air does not significantly change except for its water vapor content, which varies from 0 to 5% of the air volume. Whenever water vapor content might seriously affect the measurement, then the mathematical equations will indicate the corrective calculations that need to be made.

Special efforts have been made to use consistent symbols throughout the report. The subscripts used to indicate, for example, whether a volumetric flowrate (Q) is that measured under calibration conditions (Q_c) or at ambient, or actual, conditions (Q_a) are important. The same holds true for many of the other specified properties or qualities of the air being measured. The Summary Table contains the essential information on the various flow measurement devices which should help give an overall perspective.

II. SUMMARY

This report contains in a condensed form the basic mechanical and theoretical principles of air flow measurement devices commonly used in air pollution control monitors. The first part is devoted to a review of the composition and properties of the atmosphere. Air, to a large extent, behaves as an ideal gas. Simple temperature, pressure and volume relationships hold for most ambient air conditions. Volume ratios such as parts per million (ppm) or parts per billion (ppb) are shown to be easy to calculate. The mole-volume concept is described in such a manner as to make weight-volume conversions from parts per million to micrograms per cubic meter ($\mu\text{g}/\text{m}^3$), and vice versa, easy to perform. The role of water vapor in the air is also explained in absolute and relative humidity terms.

The latter part of this report describes in sequence the physical and mechanical features, as well as the theoretical and applied air flow relationships, of primary, intermediate, and secondary standards. The primary standards which are described and discussed include spirometers, frictionless pistons, aspirator bottles, and pitot tubes. The intermediate standards include wet and dry test meters, and the "Roots" type volume displacement meters. The secondary standards include velocity type meters such as rotameters, orifice meters, hot wire anemometers and pressure transducers. The Summary Table which follows includes pertinent relationships of the various meters and appears in this section for convenience.

Table VIII. Summary of Flowmeter Characteristics

Meter Type	Measurement Principle	Theory	Temperature - Pressure Corrections
<u>Primary Standards</u>			
Spirometers	Volume Displacement	$V_g = V_m$ $= V_{bo} - V_{mt} + V_e$	$Q_m = V_m/t$ $Q_{std} = Q_m \frac{P_m}{P_{std}} \frac{T_{std}}{T_m}$ $Q_a = Q_m \frac{P_m}{P_a} \frac{T_a}{T_m}$
Frictionless Pistons: Mercury Seal	Volume Displacement	$V_g = V_m$	$Q_m = V_m/t$ $Q_{std} \text{ and } Q_a \text{ as above}$
Frictionless Pistons Soap Bubble Flow Meter	Volume Displacement	$V_g = V_m - V_w$ $= V_m \frac{P_b - P_w (1 - RH)}{P_b}$	$Q_m = V_g/t$ $Q_{std} \text{ and } Q_a \text{ as above}$
Aspirator Bottles	Volume Displacement	$V_g = V_{bt} - V_w$ $= V_{bt} \frac{P_b - P_w (1 - RH)}{P_b}$	$Q_m = V_g/t$ $Q_{std} \text{ and } Q_a \text{ as above}$
Standard Pitot Tubes	Velocity Impact of Air	$\text{Velocity} = \sqrt{2Gh}$ $= K_p C_p \sqrt{\Delta P} \sqrt{\frac{T_q}{P_q}}$	$Q_a = (\text{Velocity}) \times (\text{Cross-Sectional Area})$ $Q_{std} = Q_a \frac{P_a}{P_{std}} \frac{T_{std}}{T_a}$
"S" - Type Pitot Tubes*	Velocity Impact of Air	$(\text{Theory same as above})$ $C_{p_{s-type}} = C_{p_{std}} \sqrt{\frac{\Delta P_{std}}{\Delta P_{s-type}}}$	$Q = (\text{Velocity}) \times (\text{Cross-Sectional Area})$ $Q_{std} \text{ as in Standard Pitot Tube}$
* These are secondary standards			
<u>Intermediate Standards</u>			
Wet Test Meters	Volume Displacement	$V_g = V_m - V_{\Delta P_m} - V_w$ $= V_m \frac{P_b - \Delta P_m - P_w (1 - RH)}{P_b}$	$Q_g = V_g/t$ $Q_{std} \text{ and } Q_a \text{ as above}$
Dry Test Meters	Volume Displacement	$V_g = V_m - V_{\Delta P_m}$ $= V_m \frac{P_b - \Delta P_m}{P_b}$	$Q_g = V_g/t$ $Q_{std} \text{ and } Q_a \text{ as above}$
Rotary Displacement Meters (Roots Meters)	Volume Displacement	$V_g = V_m - V_{\Delta P_m}$ $= V_m \frac{P_b - \Delta P_m}{P_b}$	$Q_g = V_g/t$ $Q_{std} \text{ and } Q_a \text{ as above}$

Table VIII. Summary of Flowmeter Characteristics (Continued)

Meter Type	Measurement Principle	Theory	Temperature - Pressure Corrections
<u>Secondary Standards</u>			
Rotameters	Variable Area Velocity Meters	<p>Wt. Float - Buoyancy = Drag Force</p> $V_f G (\rho_f - \rho_g) = \frac{C A_f \rho_g v_m^2}{2}$ $v_m = \sqrt{\frac{2 V_f G (\rho_f - \rho_g)}{C A_f \rho_g}}$ $Q_c = A_m v_m$ <p>= Function of ΔH</p>	<p>Theory</p> $Q_a = Q_c \sqrt{\frac{P_c}{P_a} \frac{T_a}{T_c}}$ <p>Experimental</p> $Q_a = Q_c \left[1 + C'_D (P_c - P_a) \right]$ $C'_D = 8 \times 10^{-4} \text{ Liter/mm Hg}$ <p>Q_{std} as in Standard Pitot Tube</p>
Orifice Meters	Pressure drop across constriction in gas line	<p>Pressure Drop is a Function of Gas Velocity, Density, Specific Heat, and Viscosity</p> $Q_w = E \alpha A_o G \sqrt{\frac{2 \rho_g \Delta H}{1 - m^2}}$ <p>(Plot ΔH vs known Q_c)</p>	$Q_a = Q_c \sqrt{\frac{P_c}{P_a} \frac{T_a}{T_c}}$ <p>Q_{std} as in Standard Pitot Tube</p>
Capillary Meters	Pressure drop across capillary	$Q = \frac{\pi \Delta H \left[1 + \frac{\Delta H}{2 P_2} r^4 \right]}{8 \mu L}$ <p>(Plot ΔH vs known Q_c)</p>	$Q_a = Q_c \sqrt{\frac{P_c}{P_a} \frac{T_a}{T_c}}$ <p>Q_{std} as in Standard Pitot Tube</p>
Critical Orifice	Maximum obtainable flowrate through a small orifice	$Q_{w-max} = \alpha A_o P_1 \left[\frac{G \gamma M W}{R T} \frac{2}{\gamma + 1} \right]^{\frac{\gamma}{\gamma - 1}} \left[\frac{\gamma + 1}{\gamma - 1} \right]^{\frac{\gamma}{\gamma - 1}}$ $= \frac{K \alpha A_o P_1}{\sqrt{T}}$	<p>Theory</p> $Q_{a-max} = Q_{c-max} \frac{P_a}{P_c} \sqrt{\frac{T_c}{T_a}}$ <p>Experimental</p> $Q_{a-max} = Q_{c-max} - C'_D \Delta P$ <p>C'_D for needle gauge no.</p> <p>18 = 1.1 ml/mm Hg 20 = 0.47 ml/mm Hg 22 = 0.38 ml/mm Hg 24 = 0.35 ml/mm Hg 27 = 0.12 ml/mm Hg</p>
Hot Wire Anemometer	Loss of heat from hot wire related to mass flow of air	$H = k \theta + (2 \pi k C_v \rho d v)^{\frac{1}{2}} \theta$ <p>Response is not linear with flowrate, but may be electronically adjusted to be</p>	<p>Meter may be calibrated to give volumetric flowrate at standard temperature and pressure (Q_{std}).</p> $Q_a = Q_{std} \frac{P_{std}}{P_a} \frac{T_a}{T_{std}}$
Pressure Transducer (Magnehelic Gauge)	Velocity Impact Air	Same as standard pitot tube above	$Q_a = Q_m \sqrt{\frac{T_m}{T_a} \frac{P_a}{P_m}}$

III. BASIC PRINCIPLES

THE ATMOSPHERE

The atmosphere is a gaseous mixture composed largely of nitrogen and oxygen which envelopes the earth in a thin layer. It is held by gravity, but moves easily in complex patterns depending upon the earth's rotational forces, topography, and the sun's energy. The atmosphere thins rapidly with increasing elevation. More than half of the air lies below 3.5 miles and less than 1% exists above 18 miles.

STRUCTURE

At least three classification systems are used to describe the atmosphere [Figure 1]. These are based on a) molecular composition, b) thermally related regions, and c) chemical and physical properties.

The molecular composition classification divides the atmosphere into two regions: the homosphere and the heterosphere. The homosphere extends to some 55 miles and is distinguished by the uniformity of its composition. On a dry basis, the air in the homosphere is often treated as a single gas with a molecular weight of 28.96. Above the homosphere, the heterosphere includes successive layers which contain increasing relative amounts of nitrogen, atomic oxygen, helium and hydrogen, respectively.

The thermal regions include the more popular classifications of troposphere, stratosphere, mesosphere, and thermosphere. The pauses, as shown on Figure 1, refer to the transition zones between the regions.

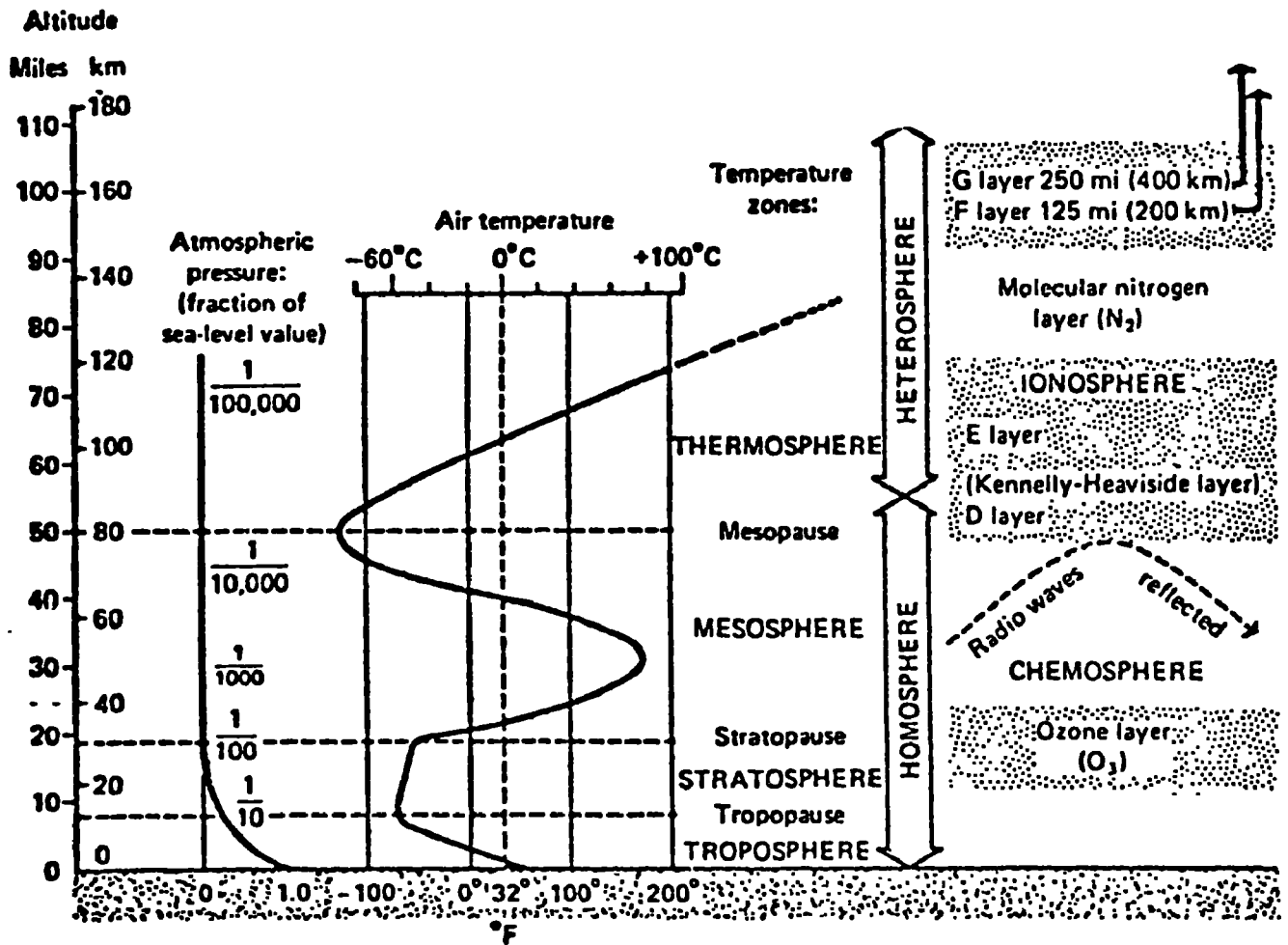


Figure 1.
Structure of the Atmosphere

The troposphere envelopes the biosphere of the earth and contains all weather phenomena. The stratosphere includes a stable "stratified" temperature region above the troposphere and forms an oxidative sink for air contaminants as well as a filter for high energy sun rays.

The chemical-physical view of the atmosphere classifies the lower part of the atmosphere as a chemosphere, or a region where chemical reactions occur. The upper part is considered a highly ionized region or ionosphere. Radio and television waves are reflected from this region.

COMPOSITION OF AIR

The composition of clean, dry air is uniform throughout the homosphere except for slight variations in the trace gases [Table 1]. On a dry-volume basis, air is nearly 78% nitrogen, 21% oxygen, and 1% argon. All the other components including carbon dioxide do not amount to over 0.04%. Their concentrations are generally expressed as parts per million rather than as percentages.

Water vapor is often a major component of air and its presence should always be taken into consideration. Because its concentration varies widely, from 0.02% to as much as 6%, it is rarely cited as an important component. The same is true for particulate matter which can vary in concentration from 15 $\mu\text{g}/\text{m}^3$ in remote regions of the ocean to 2,700 $\mu\text{g}/\text{m}^3$ and more in polluted areas.

Polluted atmospheres contain a wide variety of gases and particulate matter. Table 2 compares the concentrations of the more common pollutant gases in clean air with their concentrations in typically polluted atmospheres. The actual concentrations can vary quite widely depending on nearness to emission sources, wind direction, velocity,

Table 1
COMPOSITION OF CLEAN DRY AIR (V/V)

Gas	%	ppm
Nitrogen (N ₂)	78.09	
Oxygen (O ₂)	20.94	
Argon (Ar)	0.93	
Carbon Dioxide (CO ₂)	0.03	320
Neon (Ne)		18
Helium (He)		5.2
Methane (CH ₄)		1.5
Krypton (Kr)		1
Nitrous Oxide (N ₂ O)		0.5
Hydrogen (H ₂)		0.5
Xenon (Xe)		0.08
Ozone (O ₃)	0.01-0.04	

Table 2
COMPARISON OF TRACE GAS CONCENTRATIONS

Gas	Clean Air ppm	Polluted Air ppm	Ratio	
			Polluted to	Clean
Carbon Dioxide (CO ₂)	320	400	1.3	
Carbon Monoxide (CO)	0.1	40-70	400-700	
Methane (CH ₄)	1.5	2.5	1.3	
Nitrous Oxide (N ₂ O)	0.25	(?) ^a		
Nitrogen Oxides (NO ₂) (NO _x)	0.001	0.2	200	
Ozone (O ₃)	0.02	0.5	25	
Sulfur Dioxide (SO ₂)	0.0002	0.2	1,000	
Ammonia (NH ₃)	0.01	0.02	2	

a Not well known.

and turbulence. Particulate matter in polluted atmospheres can vary widely in composition, size distribution patterns, and concentration.

THE GAS LAWS

At ambient temperatures and pressures, most gaseous substances in the atmosphere may be considered to obey the perfect gas laws. This is because the partial pressures of all but the heaviest molecular weight (MW) substances are well below their saturation vapor pressure.

At a given temperature and pressure, all gaseous molecules occupy essentially the same volume regardless of their atomic or molecular weight. This is because their molecular size is much smaller than their mean free path. Hence, a gram mole of most gases (i.e., 2 grams of H₂; 32 grams of O₂; 44 grams of CO₂; 131 grams of Xe, etc.) occupies 22.4 liters of space at 0°C (273°K) and 760 mm pressure and contains 6.02×10^{23} molecules.

This leads to the following relationships for a given gas mixture:

$$\text{Volume \%} = \text{pressure \%} = \text{molecule (mole) \%} \neq \text{weight \%}$$

For a given parcel of gas, Charles' and Boyle's Laws state that the pressure times the volume divided by the absolute temperature is a constant. Hence, for a gas under different conditions of temperature and pressure, 1 and 2:

$$\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2} = \text{constant} \quad [1]$$

A "universal" gas constant (R) has been developed from the above relationship for a mole of a gas under standard temperature and pressure conditions.

$$\left(\frac{PV}{T}\right)_{STP} = \text{constant} = R \quad [2]$$

The constant, R, may have several numerical values depending on the units used for P, V, and T (i.e., mm Hg or lb/in² for P, liters, milliliters, or cubic feet for V and °Kelvin or °Rankine for T).

For any amount of gas which may be more or less than one mole:

$$\left(\frac{PV}{T}\right)_{STP} = R' = nR \quad [3]$$

where R' is a constant for the given amount of gas and n is equal to the number of moles of the given gas:

$$n = \frac{\text{Weight of Gas}}{\text{Molecular Weight of Gas}} \quad [4]$$

Equation 3 combined with equation 1 becomes what is commonly called the ideal gas law expression.

$$PV = nRT \quad [5]$$

For use in air flow measurement, the density (ρ) of any gas can be obtained from equations 4 and 5.

$$\begin{aligned} \rho &= \frac{\text{Weight of Gas}}{\text{Volume}} \\ &= \frac{P \cdot MW}{RT} \end{aligned} \quad [6]$$

For a given gas under different temperature and pressure conditions

$$P_1 = P_2 \frac{P_1}{T_1} \frac{T_2}{P_2} \quad [7]$$

In gaseous mixtures (such as air) the total pressure is equal to the sum of the pressures of each of its components.

$$P_{\text{total}} = P_{\text{N}_2} + P_{\text{O}_2} + P_{\text{H}_2\text{O}} + \text{etc.} \quad [8]$$

The gases of clean, dry air form an ideal mixture whose composition varies but little throughout the troposphere. Because of this composition, a "molecular" weight of air is calculated from the molecular weights of the individual gases times their respective percentages.

$$\begin{aligned} \text{MW}_{\text{air}} &= [28(\% \text{ N}_2) + 32(\% \text{ O}_2) + 40(\% \text{ Ar}) + 44(\% \text{ CO}_2) + \text{etc.}] \div 100 \quad [9] \\ &= 28.96 \\ &\approx 29.0 \end{aligned}$$

THE MOLE

The mole is a most useful concept in chemistry and physics. The gram mole refers to that amount of an element or compound whose mass (or weight) is equal to the formula weight. Because atomic weights and, consequently, the molecular (or formula) weights are

based on relative mass on a per-atom basis, the aggregate result is that a gram mole of any element or compound contains the same number of atoms or molecules. This number turns out to be 6.022×10^{23} and is called Avogadro's number.

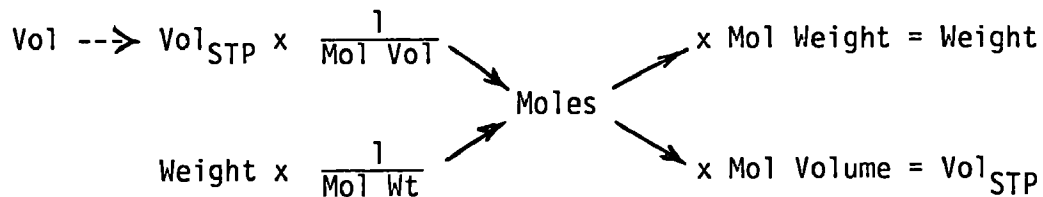
As stated above, gaseous molecules at a given temperature and pressure occupy essentially the same amount of space irrespective of mass. Thus, 6.022×10^{23} molecules, or one gram mole, of any gas occupies 22.4 liters of volume at 0°C (273° Kelvin) and 760 mm Hg pressure. Avogadro's number is a huge number. A simple calculation shows that one cubic centimeter of air contains 2.4×10^{19} molecules at 25°C and one atmosphere. What is still more interesting is that if a pollutant, such as hydrogen sulfide, were in air at a concentration of one-tenth part per billion, it could not be detected by smell, but one cubic centimeter of the polluted air would contain 2.4 billion (2.4×10^9) hydrogen sulfide molecules. This latter number is quite large, but making analytical contact with the specific molecules in the presence of billions of times as much other molecules is, at present, a very difficult task.

The mole is not limited to the gram as a unit of mass. The pound mole and, in some cases, the ton mole is used extensively in the English system. A pound mole is simply the same relative mass based on molecular or formula weights but measured in pounds rather than grams. Since 1 pound equals 453.6 grams, then a pound mole occupies 453.6 times as much volume (10,161 liters or 359 ft^3 at STP) and has 453.6 times as many molecules (2.732×10^{26}). In the English system, 70°F or 530°R is taken as the standard temperature, and the pound mole occupies 387 ft^3 at this temperature and one atmosphere pressure. For example, a gram mole of oxygen ($\text{MW} = 32$) weighs 32 grams, has 6.022×10^{23} molecules and occupies 22.4 liters at 273°K and 760 mm pressure; a pound mole of oxygen ($\text{MW} = 32$), on the other hand,

weighs 32 pounds, has 2.732×10^{26} molecules, and occupies 387 ft^3 at 530°R (70°F) and 760 mm pressure.

WEIGHT-VOLUME RELATIONSHIPS

The mole is very convenient for making weight to volume or volume to weight conversions. The weight of any substance or the volume of any gas can readily be converted to moles. The number of moles of that substance can then be converted to volume by multiplying by the molar volume ($22.4 \text{ liters/gram mole}$ or $359 \text{ ft}^3/\text{lb mole}$ at STP). The conversion of moles to weight is readily achieved by multiplying by the molecular weight.



where:

Vol = volume of given gas, any temperature and pressure

Vol_{STP} = volume at standard temperature and pressure

Mol Vol = mole volume (22.4 liter or 359 ft^3 at STP)

Weight = weight of given substance (grams or lbs)

Mol Wt = molecular (or formula) weight of substance

CONCENTRATIONS

Concentrations in air are frequently expressed as weight (mass) per unit volume such as micrograms per cubic meter ($\mu\text{g}/\text{m}^3$). They are

also frequently referred to as volume (or weight) ratios such as parts per million (ppm), or parts per billion (ppb). The principles are straightforward, but some confusion does exist as to the exact meaning and relationship of the terms in common use.

In air, ratios are generally understood to be on a volume-to-volume basis unless specifically stated otherwise. Just as percentage is calculated by:

$$\text{Percent} = \frac{\text{Part}}{\text{Whole}} \times 100 \text{ (usually volume } \div \text{ volume in air)}$$

then:

$$\text{ppm} = \frac{\text{Part}}{\text{Whole}} \times 10^6 = \text{percent} \times 10^4$$

$$\text{ppb} = \frac{\text{Part}}{\text{Whole}} \times 10^9 = \text{ppm} \times 10^3$$

$$\text{Weight \%} = \text{Vol \%} \left(\frac{\text{Mol Wt}}{29} \right) \text{ Gases in Air}$$

$$\% \text{ wet} = \% \text{ dry} \frac{(100 - \% \text{ H}_2\text{O})}{100}$$

$$\mu\text{g}/\text{m}^3 = \text{ppm} \times 40.9 \times \text{MW (at } 25^\circ\text{C, 1 atm)}$$

$$\mu\text{g}/\text{m}^3 = \text{ppm} \times 16.04 \times \frac{P_a}{T_a} \times \text{MW (at any } T_a, P_a)$$

where:

P_a = ambient pressure, mm Hg

T_a = ambient temperature °K

MW = molecular weight

DERIVATION OF MASS-RATIO RELATIONSHIP

In deriving the mass-ratio relationship it is convenient to use the assumption that one liter of a given pollutant (x) exists per one million (10^6) liters of air for each part per million of x (ppm_x).

$$\text{Vol}_x = \text{ppm}_x \cdot \frac{1 \text{ liter}_x}{10^6 \text{ liter}_{\text{air}}} \quad [10]$$

To convert this volume to weight, the volume is adjusted to standard temperature and pressure (STP: 273°K, 760 mm Hg).

$$\text{Vol}_{x\text{STP}} = \text{ppm}_x \cdot \frac{1 \text{ liter}_x}{10^6 \text{ liter}_{\text{air}}} \cdot \frac{T_{\text{STP}}}{T_x} \cdot \frac{P_x}{P_{\text{STP}}} \quad [11]$$

The volume of x is then changed to moles of x.

$$\text{Moles } x = \text{ppm}_x \cdot \frac{1 \text{ liter}_x}{10^6 \text{ liters}_{\text{air}}} \cdot \frac{T_{\text{STP}}}{T_x} \cdot \frac{P_x}{P_{\text{STP}}} \cdot \frac{1 \text{ mole}_x}{22.4 \text{ liters}_x} \quad [12]$$

The moles of x are subsequently converted to weight by multiplying by the molecular weight of x (MW_x) which gives the weight in grams. This is converted to micrograms by multiplying by the factor $10^6 \mu\text{g}/\text{gram}$ and to cubic meters of air by the factor 1,000 liters air/m^3 . The entire equation becomes:

$$\begin{aligned} \text{Wt}_x/\text{m}^3 &= \text{ppm}_x \cdot \frac{1 \text{ liter}_x}{10^6 \text{ liter}_{\text{air}}} \cdot \frac{T_{\text{STP}}}{T_x} \cdot \frac{P_x}{P_{\text{STP}}} \cdot \frac{1 \text{ mole}_x}{22.4 \text{ liter}_x} \cdot \\ &\quad \frac{\text{MW}_x \text{ grams}}{\text{mole}_x} \cdot \frac{10^6 \mu\text{g}}{\text{gram}} \cdot \frac{10^3 \text{ liter}_{\text{air}}}{\text{m}^3} \end{aligned} \quad [13]$$

$$= \text{ppm}_x \cdot 16.04 \cdot \text{MW}_x \frac{P_x}{T_x} \frac{\text{ug}}{\text{m}^3_{\text{air}}} \quad [14]$$

For T_x equal to 298°K (25°C) and P_x equal to 760 mm Hg,

$$\text{Wt}_x/\text{m}^3 = \text{ppm}_x \cdot 40.9 \cdot \text{MW}_x \frac{\text{ug}}{\text{m}^3_{\text{air}}} \quad [15]$$

where: $T_{\text{STP}} = 273^\circ\text{K}$
 $P_{\text{STP}} = 760 \text{ mm Hg}$
 $T_x = \text{ambient temperature, } ^\circ\text{K}$
 $P_x = \text{ambient pressure, mm Hg}$

Table 3 gives some typical applications.

PHYSICAL VOLUMES AND GASEOUS VOLUMES

In atmospheric measurements there is, at times, some confusion regarding the true concept of the volume under consideration. In some cases, the word volume is intended to represent a measured portion of space with due consideration to the air or the atmospheric pollutant occupying that volume. Such a volume may be called a physical volume. A physical volume is described by a three dimensional configuration or its equivalent. Its units are cubic inches, cubic feet, cubic meters, gallons, liters, etc. The size of such units is fixed and does not change with temperature, pressure, time, or place. Containers of such specified volumes will always measure and deliver air (or other gases) whose volume is equal to the volume of the container at the temperature and pressure of the measurement.

Table 3
TYPICAL MASS-RATIO RELATIONSHIPS

Compound	MW	$\mu\text{g}/\text{m}^3$ (25°C, 1 Atm.)			
		1 ppb	0.1 ppm	1 ppm	10 ppm $\times 10^3$
CO	28	1.15	115	1,150	11.5
NO	30	1.23	123	1,230	12.3
NO ₂	46	1.88	188	1,880	18.8
SO ₂	64	2.62	262	2,620	26.2
C ₈ H ₁₈	114	4.66	466	4,660	46.6
DDT	354	14.48	1,448	14,480	144.8

A gaseous volume, on the other hand, is considered to be that volume occupied by a specified amount of air (or gas) at a given temperature and pressure. The temperature and pressure may be the actual temperature and pressure of the air, or a standard type of temperature and pressure which may have been selected for uniformity of comparison. If so, then the volume cited would not necessarily be that of the actual air parcel but the calculated equivalent volume for the temperature and pressure selected. Such volume adjustments, when properly used, are highly desirable for uniformity of comparison and regulation.

However, overuse of standard temperature and pressure adjustments leads to loss of understanding of the spatial relationships of pollutants. Light scattering particles, for example, when collected from a cubic meter of air at high altitudes would be interpreted to be more crowded and scattering more light when the volume of the sampled air is converted to a standard temperature and pressure. For example, an atmosphere containing 50 micrograms per cubic meter at 30°C and 630 mm pressure (Denver in summer), could be interpreted to contain 61 micrograms per cubic meter at a standardized temperature and pressure of 25°C and 760 mm. Such an interpretation is simply not true both in terms of light scatter or amount of particulate matter to which a person is exposed.

Additional confusion arises when a volumetric or flowrate device is calibrated in a laboratory, has a calibration curve drawn to standard temperature and pressure, and is used in the field where the temperature and pressure may differ significantly from those of both the laboratory and standard curve.

The correction of measurements made by volumetric devices (wet and dry test meters, soap bubble flowmeters, etc.) follows simple

ideal gas law calculations. But the correction of velocity flowrate measurement devices (pitot tubes, rotameters, orifice meters, etc.) is not straightforward and must be made with proper precautions. If at all feasible, flowrate measurement devices should be calibrated in the field reasonably close to where they are being used. This is not always possible in spot sampling, balloon and aircraft measurements, for example. In any event, due caution must be exercised in order that the reported data reflect either a measurement of an event or substance occurring with a given unit of space (physical volume) or occurring within a given unit of air (gaseous volume). The former reflects properties of a given place or environment, while the latter reflects the relative quantity per standard unit of volume. Improper use of either concept can lead to erroneous conclusions.

WATER VAPOR

The amount of water vapor in air is highly variable. It depends on the nearness of water bodies, soil moisture, vegetative cover, wind direction, ambient temperature, etc. It may be present from a low of 0.1% (200 ppm) in arid regions or at low temperatures, to as high as 6% (60,000 ppm) in warm, humid climates.

The water vapor content of the air is generally measured as percent relative humidity and is calculated as the percent of the saturation vapor pressure of water that is present at the given temperature.

$$\% \text{ RH} = \frac{\text{Water Vapor Pressure}}{\text{Saturated Water Vapor Pressure}} \times 100 \quad [16]$$

The relative humidity does not indicate the actual amount of water vapor that is present. At 50% relative humidity, for example,

the actual amount of water in the air would be approximately 3% (30,000 ppm) at 100°F and only 0.06% (600 ppm) at 0°F. Table 4 gives the saturation vapor pressure of water over the general tropospheric range of temperatures.

More commonly the relative humidity is obtained from wet bulb-dry bulb temperature measurements (or other similarly related physical measurements) where the difference between the measurements is a function of the relative humidity rather than the absolute humidity of the air.

Relative humidity, however, is an important parameter in that it gives a measure of the tendency of water to adsorb on, or evaporate from, condensation nuclei, solid surfaces, liquid droplets, etc. As temperatures drop, the relative humidity increases for a given amount of moisture in the air. When 100% relative humidity is attained, water vapor condenses spontaneously and the "dew point" is said to be attained.

The water molecule is highly polar and readily adsorbs on most materials to form mono- or multiple molecular layers of adsorbed water, even at low relative humidities. At higher relative humidities >60% relatively thick layers of water are adsorbed and atmospheric aerosols are observed to increase significantly in size.

Many pollutant gases dissolve in the adsorbed water and react chemically with each other, absorbed oxygen, or with the substrate material. This is particularly true of sulfur dioxide which readily dissolves in water to react catalytically with absorbed oxygen and water to form sulfuric acid. The acid thus formed is corrosive to metals, various industrial and commercial materials, and plays an important role in the increase of the acidity in rainwater.

Table 4
WATER VAPOR PRESSURE AS A FUNCTION OF TEMPERATURE

°C	°F	Vapor Pressure mm Hg
-40	-40	0.97 ^a
-30	-22	0.29 ^a
-20	- 4	0.78 ^a
-17.8	0	0.96 ^a
-10	14	1.95 ^a
0	32	4.58
5	41	6.54
10	50	9.21
15	59	12.8
20	68	17.5
25	77	23.8
30	86	31.8
35	95	42.2
40	104	55.3
45	113	71.9
50	122	92.5
55	131	118
60	140	149

a Vapor pressure given is that of ice at the given temperature.

IV. AIR FLOWRATE AND VOLUME MEASUREMENTS

Flowrate and volume measurements when used for the collection and estimation of the concentrations of atmospheric pollutants often contribute a major portion of the uncertainty in the reliability of the measurement. Involved are not only the accuracy and magnitude of the response of the measuring device to airflow variations, but also the effects of changes in temperature, atmospheric pressure, relative humidity, flow patterns and pressure drop changes due to the accumulation of collected or deposited matter on filters, regulating valves, floats, and other moving parts. To minimize such errors, an understanding of the operating principles and the effects of the operational and environmental variables is important.

Instruments used for calibrating and measuring air flowrates may be described according to several possible categories. In this case, they have been grouped as: primary standards; intermediate standards; and secondary standards. Except for the pitot tube, the primary standards are volume displacement meters wherein the metering volume can be measured directly and accurately. Such meters include spirometers, frictionless pistons, and aspirator bottles. The internal volumes of volume displacement meters are constant and do not change with temperature or pressure (altitude) except for very minor changes caused by temperature expansion coefficients of the meter materials. Often, the gaseous volumes measured by the meters are converted to some desired ambient or standard temperatures and pressure by ideal gas law calculations or by adjusted calibration curves. However, the true volume of the air being measured is a direct function of the volume of the metering chamber.

The pitot tube is a velocity measuring instrument. The theory of operation is well known, and it has long been established as a dependable standard for measuring gas flow velocities.

The intermediate standards include the wet and dry test meters and the rotary displacement meters. These are all volume displacement meters whose internal volumes cannot be measured accurately. When calibrated with primary standards or known volumes they make excellent laboratory and field volumetric flowrate devices. Temperature and pressure conversions are straightforward involving the usual ideal gas law corrections.

Secondary standards include devices that depend upon the velocity of the air to produce some physical change or force which can theoretically or empirically be related to a volumetric flowrate. Such devices include rotameters, orifice meters, hot wire anemometers, pressure transducers, and vane anemometers. Their response is often conveniently observed by visual, mechanical, or electronic means. However, the response is generally not a simple function of the flowrate of the gas alone. In addition to temperature and pressure, other factors which may be important are gas density, molecular weight, viscosity, specific coefficients of heat and flow turbulence (Reynolds numbers).

In the following sections, emphasis will be placed on those devices which are commonly used for air flow measurements. The principal factors and relationships which control and affect the measurements will be discussed and illustrated mathematically. Wherever possible, simplified formulas for temperature and pressure corrections will be given.

PRIMARY STANDARDS

Spirometers

The spirometer is perhaps the most widely accepted primary standard for airflow and volume calibrations [Figure 2]. A moveable bell whose internal volume can be accurately measured is used to collect air moving through or from a gas measuring device. The bell rises above a liquid reservoir seal [Figure 2] as the air enters. The rise of the bell gives the volume of the entering gas, and the time of flow is used to calculate the flowrate. The bell is carefully counterweighted with a cycloidal counterpoise that compensates for the decreasing buoyancy of the liquid seal as the bell rises. In some instances, the spirometer is used to deliver known volumes of air or other gases.

Most spirometers are calibrated at the factory against standards certified by the U.S. Bureau of Standards. They can also be rechecked by accurate internal measurement or against Bureau of Standards certified volumes if found necessary after damage or readjustment. For proper use, the spirometer must be carefully aligned to provide free vertical movement. All leaks must be eliminated; the liquid level must be correct; and the temperature of the liquid reservoir must not differ from the ambient air by more than 0.3°C. Proper adjustment of the cycloidal counterpoise should cause no drift of the bell when all valves are open. When calibrating a spirometer by physical measurement, the volume of the gas (V_g) is equal to the increase in the internal volume of the bell (V_{bi}), plus the drop in displacement of the liquid level as the bell rises (V_e).

$$V_g = V_{bi} + V_e \quad [17]$$

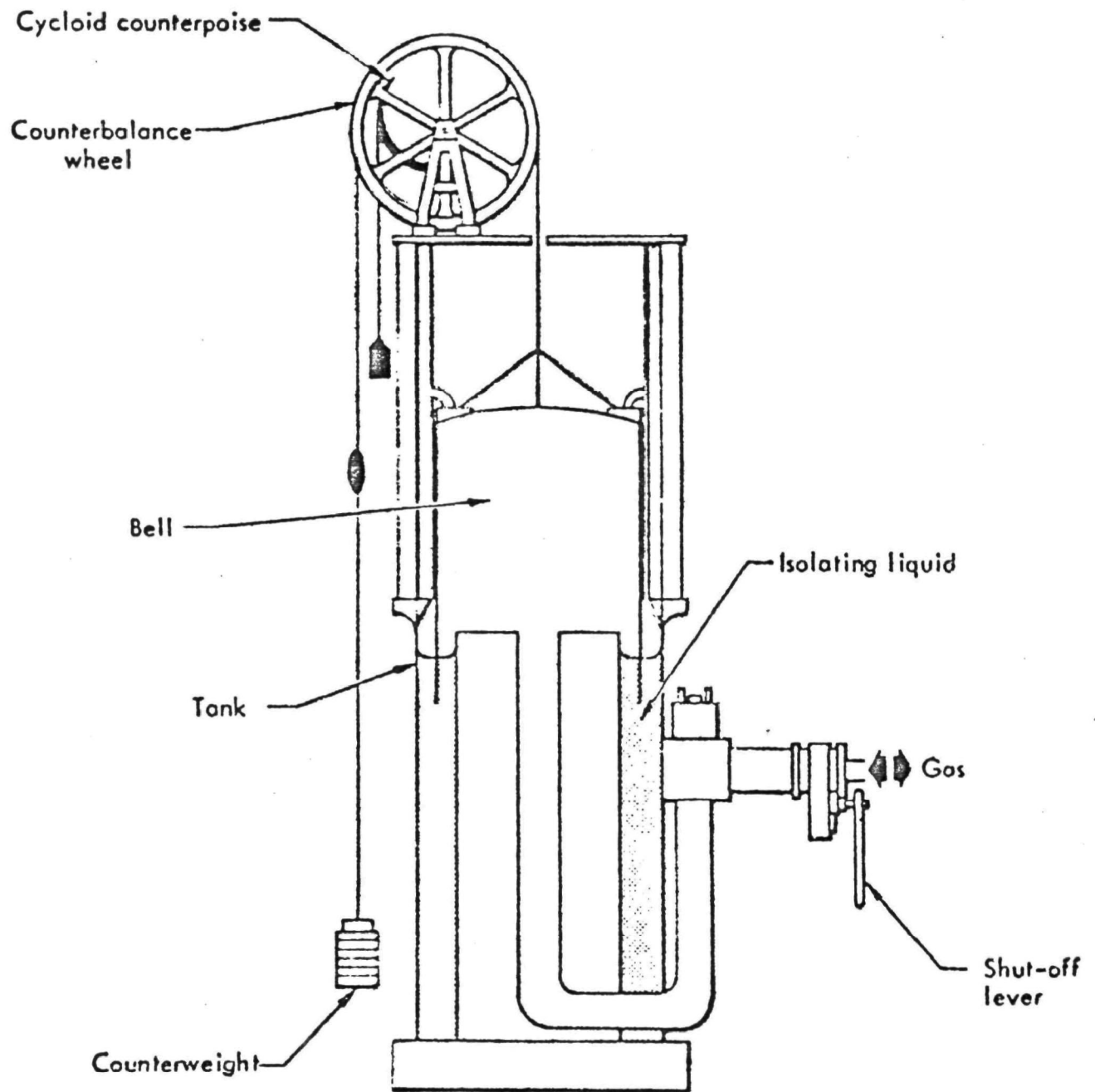


Figure 2.
Cross-Sectional View of a Spirometer

The internal volume of the bell (V_{bi}) is equal to the external volume of the bell (V_{bo}) less the volume of the metal (V_{mt}). Hence,

$$V_g = V_{bo} - V_{mt} + V_e \quad [18]$$

For a more complicated spirometric apparatus, careful evaluation of all factors, including the volumes of the inlet and outlet lines, will reduce experimental errors to a minimum.

Frictionless Pistons

Frictionless pistons furnish a convenient method of calibrating gas flowrates and volumes. The mercury-sealed piston [Figure 3] is a simple, directly observable device for measuring small volumes or low gas flowrates. The volume of the piston can readily be calibrated by directly weighing water added to or withdrawn from portions or the entire contents of the piston, much as one would calibrate a burette in quantitative analysis.

For flowrates up to several liters per minute, soap-bubble flowmeters are widely popular standards for air flow measurements. Soap-bubble flowmeters come in a variety of designs and sizes [Figure 4]. The basic principle involved is the insertion of a thin aqueous film in the path of a stream of air as it moves through a burette or graduated cylinder. The volume of either can be calibrated as was described for the mercury-sealed frictionless piston. The time of passage between marks is used to calculate the flowrate.

The film is inserted into the air stream by allowing the air to momentarily pass through a soap or surface active solution. A bubble

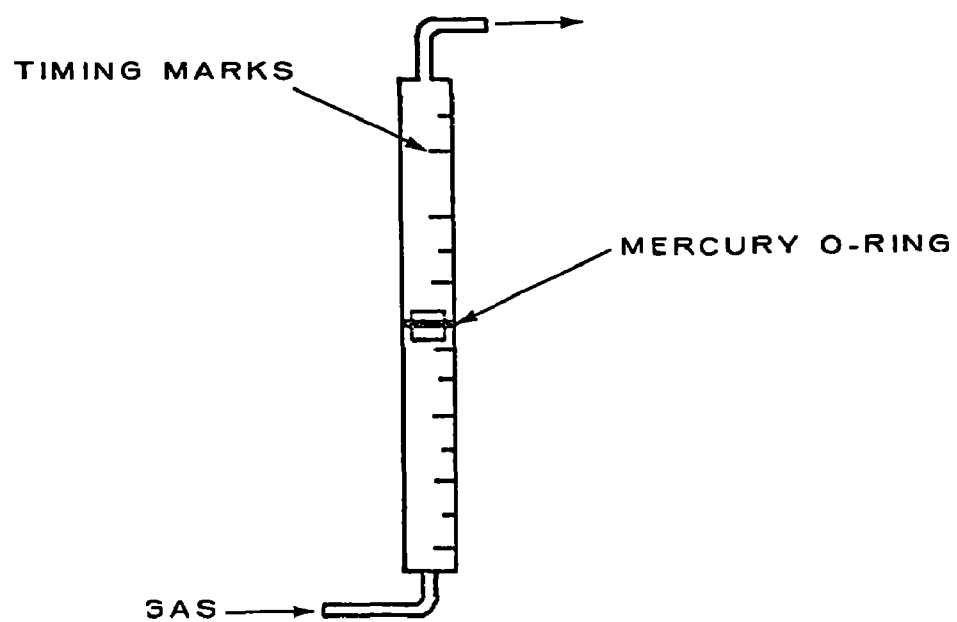


Figure 3.
Mercury-seal Piston Flowmeter

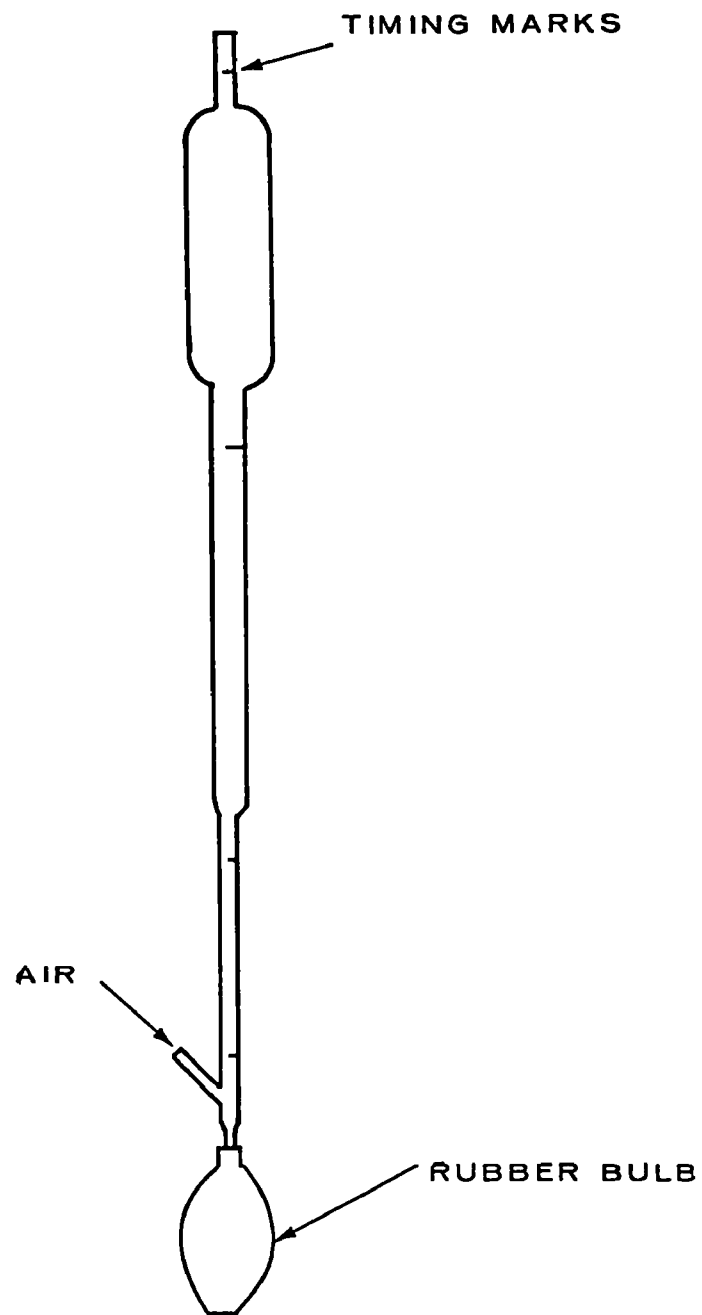


Figure 4.
Soap-bubble Flowmeter

is formed which travels through the burette at the same velocity as the air stream. It usually takes a number of bubbles before the inside of the burette is wet enough to maintain the film throughout the length of the burette. The flowmeter may be used at either the outlet or inlet ends of the metering device to be calibrated. If used at the inlet end, precautions must be taken to prevent overflow of the film or spray from bursting bubbles being carried with the air into the measuring device.

As the air (or gas) passes through the soap-bubble meter, it picks up water vapor to the saturation vapor pressure of water for that temperature. This increases the volume of the gas being measured from 0 to 4%, depending upon the temperature and the amount of moisture (relative humidity) in the original air stream. In general, this effect is ignored. It can be important, however, for dry gases at ambient and higher temperatures. Corrections for the volume increase may be calculated as follows:*

$$Q_c = Q_o \frac{P_b - P_w(1-RH)}{P_b} \quad [19]$$

Q_c = Corrected flowrate

Q_o = Observed flowrate

P_b = Barometric pressure

P_w = Saturated water vapor pressure at temperature of test

[Table 4].

RH = Relative humidity (0 to 1.00)

For dry gases, where RH = 0, equation 19 becomes:

$$Q_c = Q_o \frac{P_b - P_w}{P_b} \quad [20]$$

* It is to be noted that when the air or gas which passes through the soap-bubble flowmeter is used in any manner without drying, the water vapor correction must not be applied.

At low flowrates or when a large diameter cylinder is being used, there is a possibility that air will diffuse through the soap bubble film giving low results. This effect can be essentially eliminated by reading the movement of the second of a double or triple set of films moving with the air stream.

Aspirator Bottles

Aspirator bottles sometimes form a convenient means of flowrate measurement in the 0 to 500 ml/min range. Air flow generally is from the device to be calibrated to the aspirator bottle [Figure 5]. The air flows into the bottle at a rate that is equal to the rate that water flows out of the bottle into a graduated cylinder. Alternatively, the bottle itself may be calibrated. The air flowrate is then equated to the water flowrate.

Serious errors can be introduced by either positive or negative gas pressure changes caused by the manner that the water is allowed to flow out of the bottle. Positive pressures can be developed, for example, by air moving into the bottle faster than the water is flowing out. Negative pressures can be caused by a siphoning action if water flowing out of the bottle passes through a vertical tube. It should also be recognized that the flowrate of water out of the aspirator bottle can change when controlled by a stopcock, screw clamp, or similar flow restrictor. The pressure head of the water inside the bottle against the restrictor will decrease as the water level inside the bottle drops. This can amount to as much as 20 or more inches of water depending upon the size of the aspirator bottle.

If the relative humidity of the air (or gas) being measured is less than 1.00, the volume of the air in the aspirator bottle will

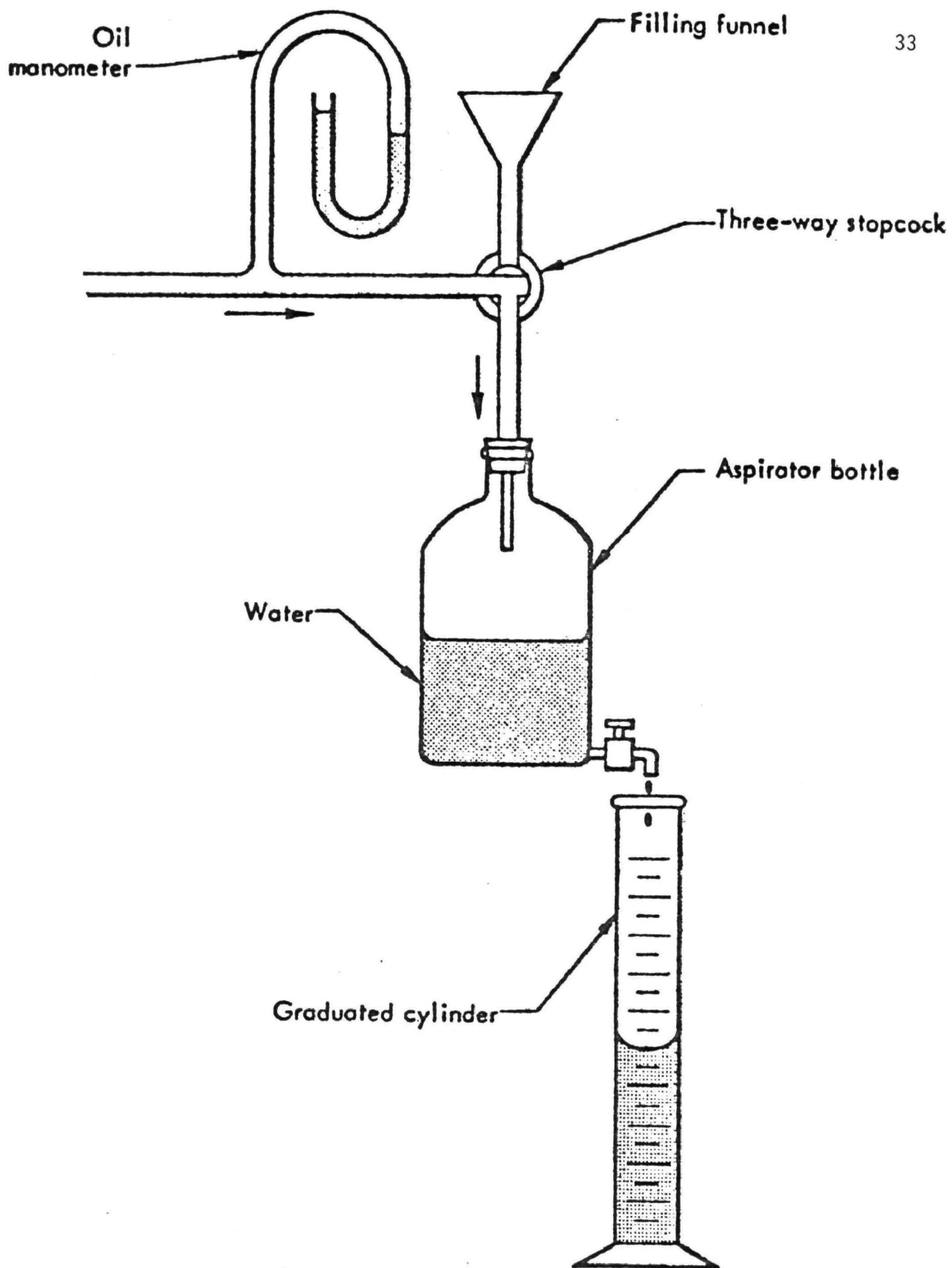


Figure 5.

Aspirator Bottle for Measuring Low Gas Flow Rates

expand depending upon the degree of equilibration and the saturation vapor pressure of the water at the temperature of the water as explained above for the soap-bubble flowmeter (Equation 19). Again, this may not amount to more than 4% error and may be ignored if other variables are not being controlled to this degree of accuracy. Indeed, of the primary calibration standards, although popular in use, this may be one of the more difficult techniques to control for high accuracy.

Pitot Tubes

Pitot tubes have been used as primary standards for measuring gas velocities for many years under wide ranges of velocities, gas types, and mixtures. Their theory is well developed and understood. Their application is widespread--in research, industry, and commerce. In its most common form, the pitot tube consists of two concentric tubes which are used to measure the differential pressure between the impact and static pressures of a moving gas stream, respectively [Figure 6].

The basic theoretical relationship for a pitot tube finds that the velocity of a moving fluid is a function of the impact velocity of the fluid. The relationship has been verified for a large number of both compressible and noncompressible fluids. When applied to air:

$$Q_a = \sqrt{2Gh_a} \quad [21]$$

Q_a = Flowrate of air

G = Force of gravity

h_a = Height of column of air supported by the impact pressure

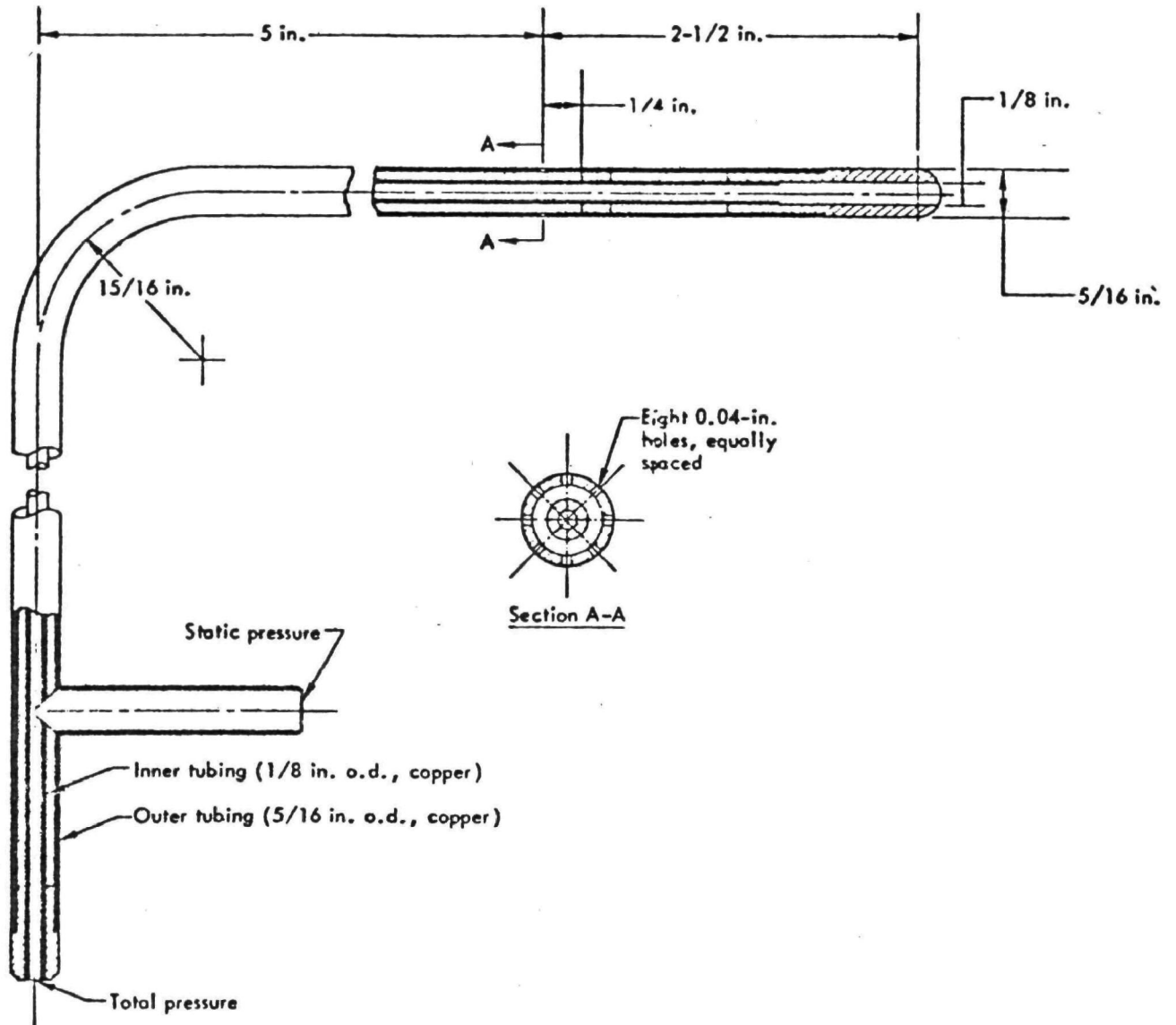


Figure 6.
The Standard Pitot Tube

The differential pressure of the moving air is generally measured by a manometer whose two arms are connected to the velocity impact and pressure tubes, respectively. For flowrates encountered in air pollution source measurements where an "S-type" pitot tube is used (see below), the manometer is usually of the inclined plane type filled with a nonvolatile colored fluid of known density. Hence the impact of the moving air which according to equation 21, above, would support a column of air (of density ρ_a) to a height of h_a , instead supports in the manometer a liquid of density, ρ_ℓ , to a height of h_ℓ . Since the height times the density of one liquid equals that of another:

$$\begin{aligned} h_a \rho_a &= h_\ell \rho_\ell \\ h_a &= \frac{h_\ell \rho_\ell}{\rho_a} \end{aligned} \quad [22]$$

Substituting for h_a from equation 22 into equation 21:

$$Q_a = \sqrt{\frac{2Gh_\ell \rho_\ell}{\rho_a}} \quad [23]$$

The density of clean, dry air (ρ_a) in equation 23 is calculated from its mole weight and volume as 28.96 grams for 22.4 liters (or 1.29 grams per liter) at 273°K and 760 mm Hg pressure as obtained from the perfect gas laws:

$$\rho_a = 1.29 \frac{273}{T_a} \frac{P_a}{760} \text{ grams/liter} = 0.463 \frac{P_a}{T_a} \quad [24]$$

P_a = Pressure of air, mm Hg

T_a = Temperature of air, °K

If, as often happens when working with air pollution emission sources, composition of the stack gases being emitted may differ considerably from air, then the density of that gas (ρ_g) may be calculated from the molecular weight of that gas relative to air.

$$\rho_g = \rho_a \frac{MW_g}{MW_a} \frac{273}{T_g} \frac{P_g}{760} \quad \text{grams/liter} \quad [25]$$

Substituting equation 25 into equation 23, one obtains a general equation for the velocity of any gas.

$$Q_g = \sqrt{\frac{2G h_{\ell} \rho_{\ell}}{\rho_a \frac{MW_g}{MW_a} \frac{273}{T_g} \frac{P_g}{760}}} \quad [26]$$

MW_g = Molecular weight of gas being measured (see equation 9)

MW_a = Molecular weight of dry air, 28.96.

For a known pressure reading device, such as an inclined manometer whose scale is adjusted to read in inches of water, many of the terms of equation 26 become known and the equation can be simplified to:

$$Q_g = K_p C_p \sqrt{\frac{\Delta P_{\ell} T_g}{MW_g P_g}} = K_p C_p \sqrt{\Delta P_{\ell}} \sqrt{\frac{T_g}{MW_g P_g}} \quad [27]$$

where ΔP_{ℓ} is the height of the manometer liquid in inches of water and K_p is a collection of the known terms of equation 26. When English units are used K_p is equal to $85.48 \text{ ft/sec (lb/lb-mole } ^\circ\text{R)}^{1/2}$. The pitot tube correction factor, C_p , is generally assumed to be 0.99 or 1.00 for the standard pitot tube and approximately 0.85 for the Stauscheibe ("S-type") pitot tube used in stack gas measurements (see below).

"S-Type" Pitot Tube

In stack gas measurements, the standard pitot tube plugs up rather easily. In its place, the federal reference method for measuring stack gas velocities uses the Stauscheibe or "S-type" pitot tube [Figure 7]. Essentially, the S-type pitot tube consists of two approximately $\frac{1}{8}$ " (6 mm) i.d. metal tubes attached to each other and bent in such a manner as to present a tapered opening directly into a flowing gas stream. This tube measures the velocity impact of the gas stream. The other tube, bent and tapered in the same manner but facing 180° from the first, measures the static pressure of the gas stream. The difference between the velocity impact and the static pressure as measured by an inclined plane liquid manometer [Figure 7] is used to calculate the gas velocity just as in the case of the standard pitot tube (equation 27). However, the pitot tube correction factor (C_p) will differ significantly from that of the standard pitot tube. The turbulence in the air stream as it passes the edges of the two tubes in essence reduces the static pressure measured by the downstream tube. This results in a high manometer reading (ΔP_ℓ). A smaller correction factor C_p , adjusts for the high reading. As indicated above, the C_p value for the S-type tubes generally is in the vicinity of 0.85. However, it should be determined for each tube and checked periodically. In particular, it should be rechecked whenever the tapered edges of the pitot tube have been bent or damaged in any manner.

The equation for calculating C_p is:

$$C_p = \frac{V}{\sqrt{\frac{2\Delta P_\ell}{\rho}}} \quad [28]$$

V = Velocity of gas stream

ρ = Density of gas

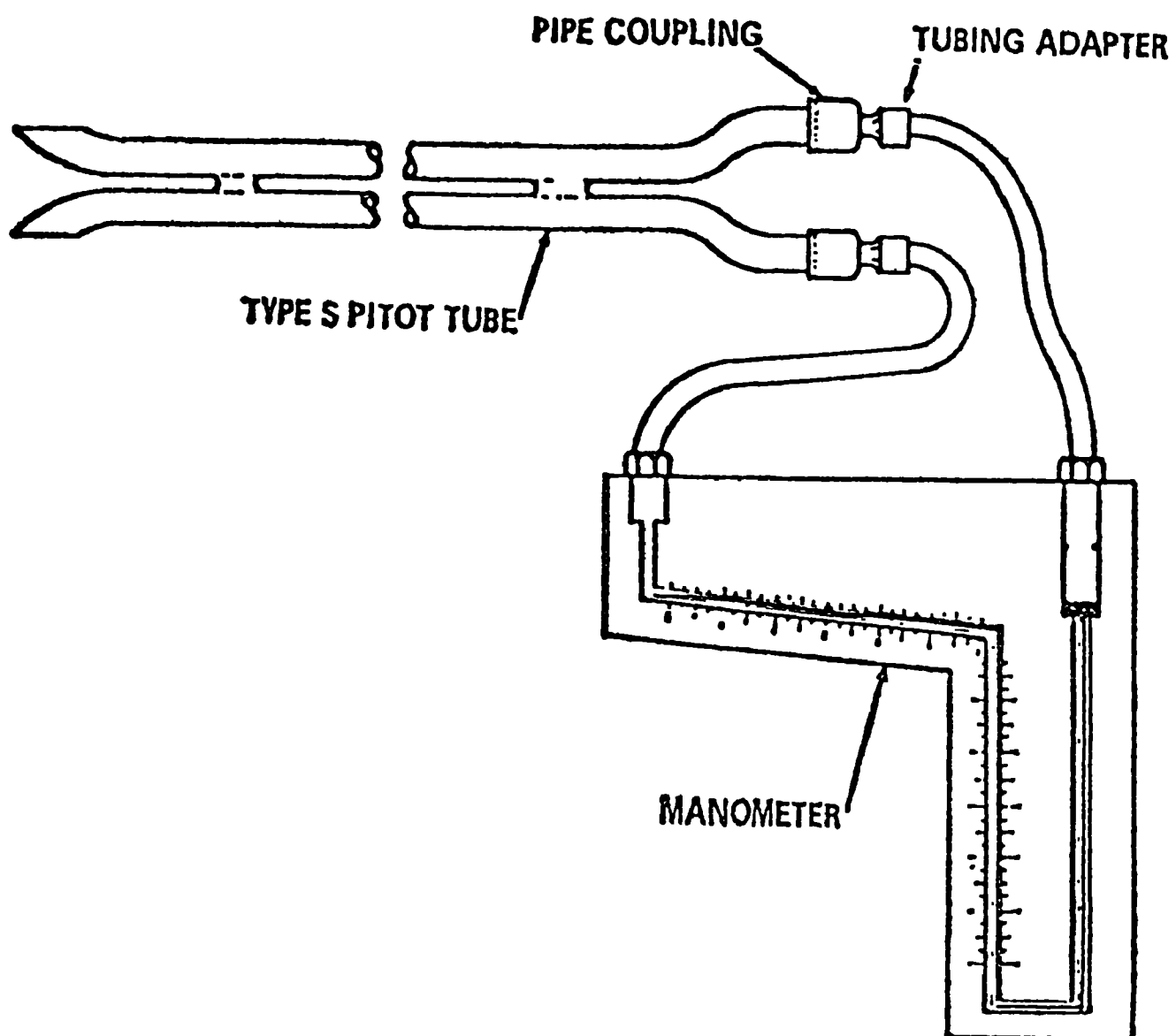


Figure 7.
"S" Type Pitot Tube and Manometer Assembly

In practice, the correction factor for the S-type pitot tube ($C_{p(S\text{-type})}$) is obtained by comparing its response to that of the standard pitot tube ($C_{p(std)}$) for the same position in the same gas stream. From equation 28 it follows:

$$C_{p(S\text{-type})} = C_{p(std)} \sqrt{\frac{\Delta P_{std}}{\Delta P_{S\text{-type}}}} \quad [29]$$

The above equation is the equation specified in the Federal Register for calibrating the S-type pitot tube used in the Federal reference method for stack sampling [Figure 8].

When measuring stack gas velocities it is not always possible to expose the velocity impact (upstream) tube perpendicularly to the direction of flow. Stack and cyclone gases near points of entry, turns, etc., will tend to swirl, pitch, and yaw. Measuring this "non-tangential" flow correctly can be difficult. Care should be taken to have the velocity impact tube opening as close to perpendicular to the direction of flow as possible. A recent study showed that the configuration shown in Figure 9 gave reproducible C_p values over $\pm 20^\circ$ variations from perpendicular flow.

INTERMEDIATE STANDARDS

Wet Test Meters

Wet test meters are used extensively in laboratories where gas flow or gas volumes are measured. They are inconvenient to use outside the laboratory and as a rule are not used in the field. They can be used directly as part of an air flow apparatus, or they can be used to calibrate secondary standards and flowrate devices.

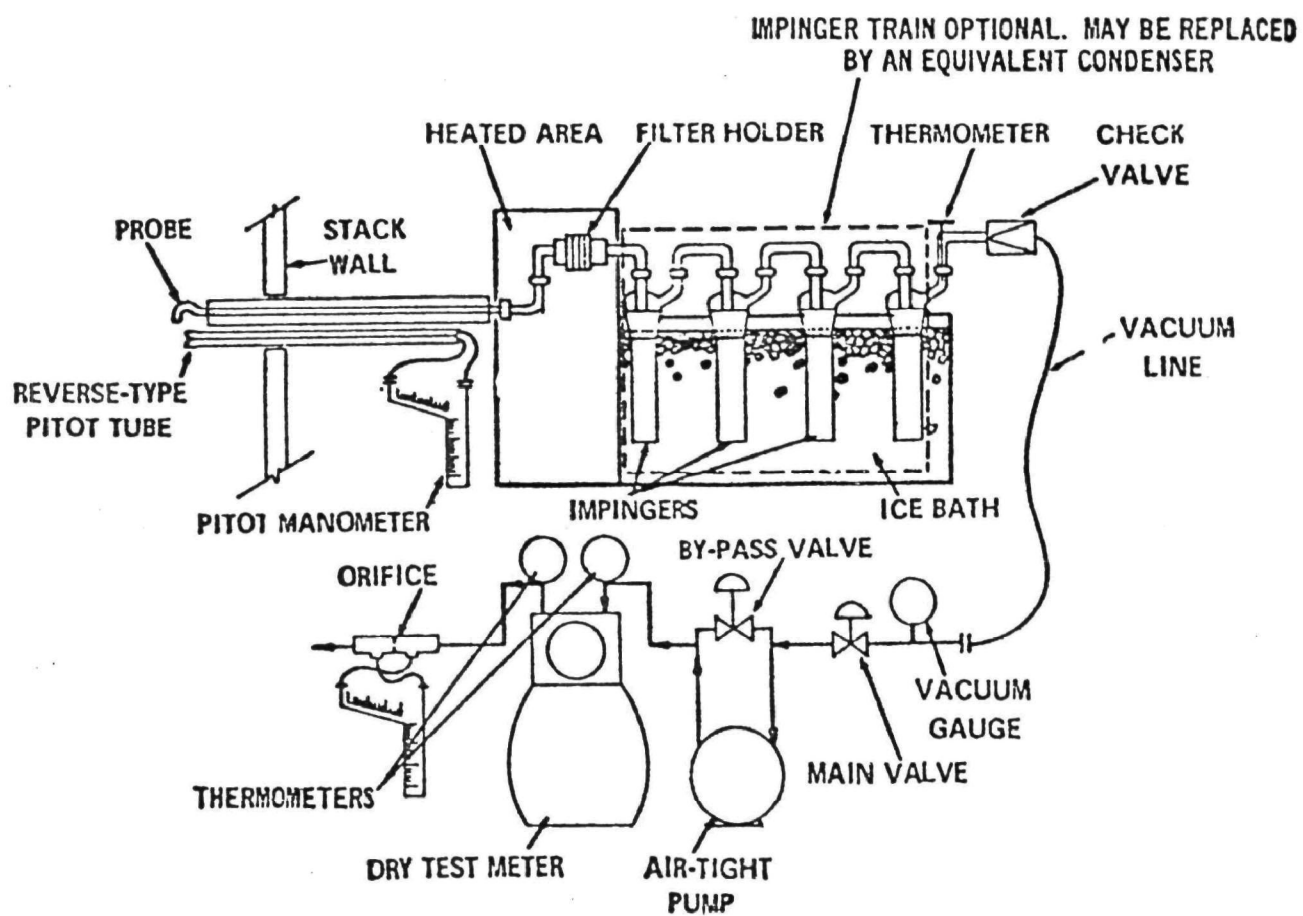


Figure 8.
Particulate Sampling Train

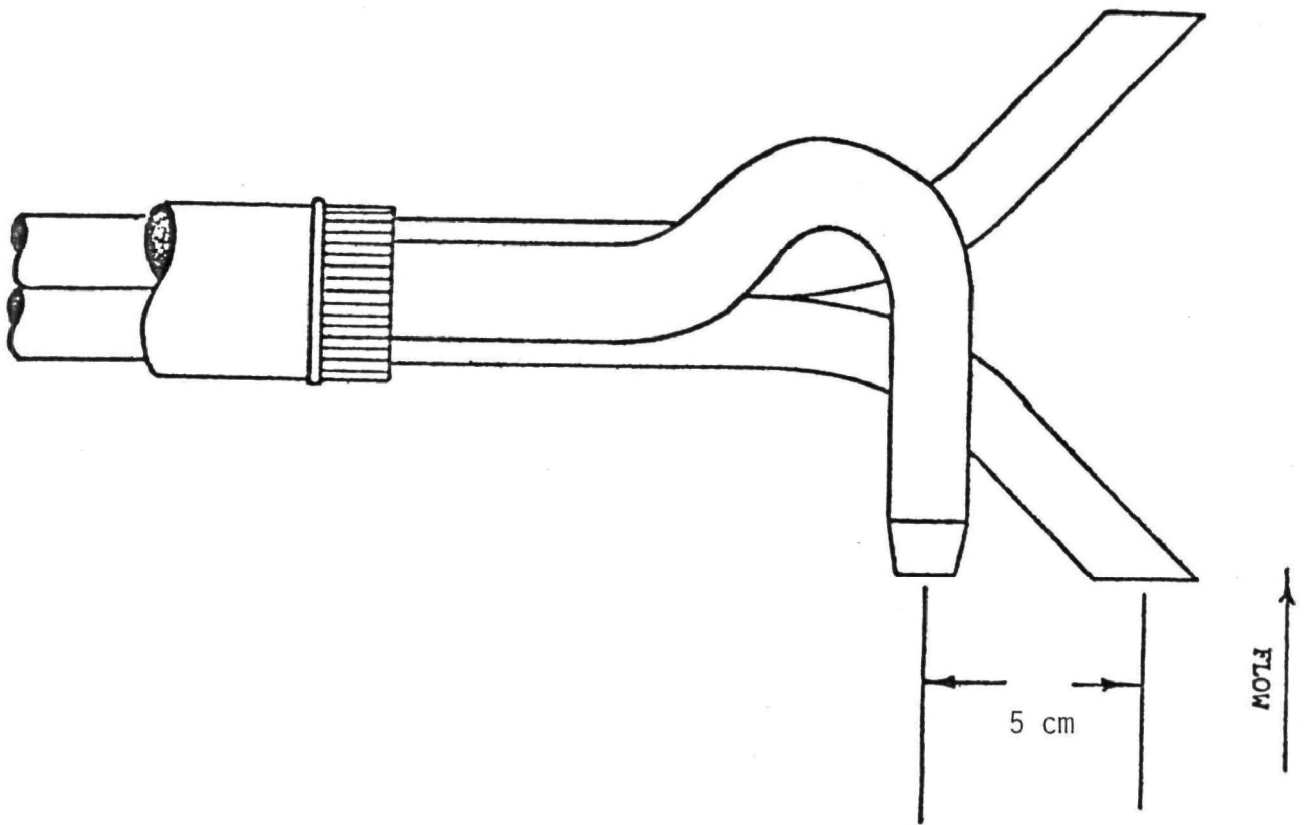


Figure 9.
Relative Positions of Sampling Probe and Pitot Tube

The wet test meters consist of cylindrical tanks of varying sizes approximately two-thirds full of water [Figure 10]. The tank contains a rotary drum that is divided into four sections. Each section contains an inlet and an outlet. The gas being measured enters at the center of the tank passing into one of the rotating sections. The buoyant force of the gas rotates the drum until the gas inlet is closed and the outlet is exposed. Gas starts to enter the following section while the gas in the first section is displaced outward as the section rotates into the water. The drum is furnished with a pointer and associated gears and dials to indicate the volume of gas that has passed through the meter. To keep the drum running smoothly, a minimum flowrate of one to two liters per minute must be maintained. Maximum flowrates are limited to less than 100 liters/min. due to excessive pressure differentials that may develop.

The meter is supplied with a water level gauge, a filling funnel, and a drain plug. The water level is critical and must be carefully adjusted to obtain the correct values. A thermometer and a water manometer give the temperature and pressure differential between the gas being measured and ambient pressures. The meter can be calibrated with a spirometer [Figure 11], a Bureau of Standards bottle of known volume, or an aspirator bottle of known volume. The volume indicated by the wet test meter should agree within 0.5 to 0.25% of the known volume.

For more precise measurements, the volume of gas indicated by the meter should be corrected for the increased amount of water vapor picked up by the gas as it passes through the meter as well as the pressure differential developed.

$$V_g = \frac{V_o}{P_b} \frac{T_a}{T_m} [P_b - 1.87 H_m - P_w (1-RH)] \quad [30]$$

* See footnote page 31.

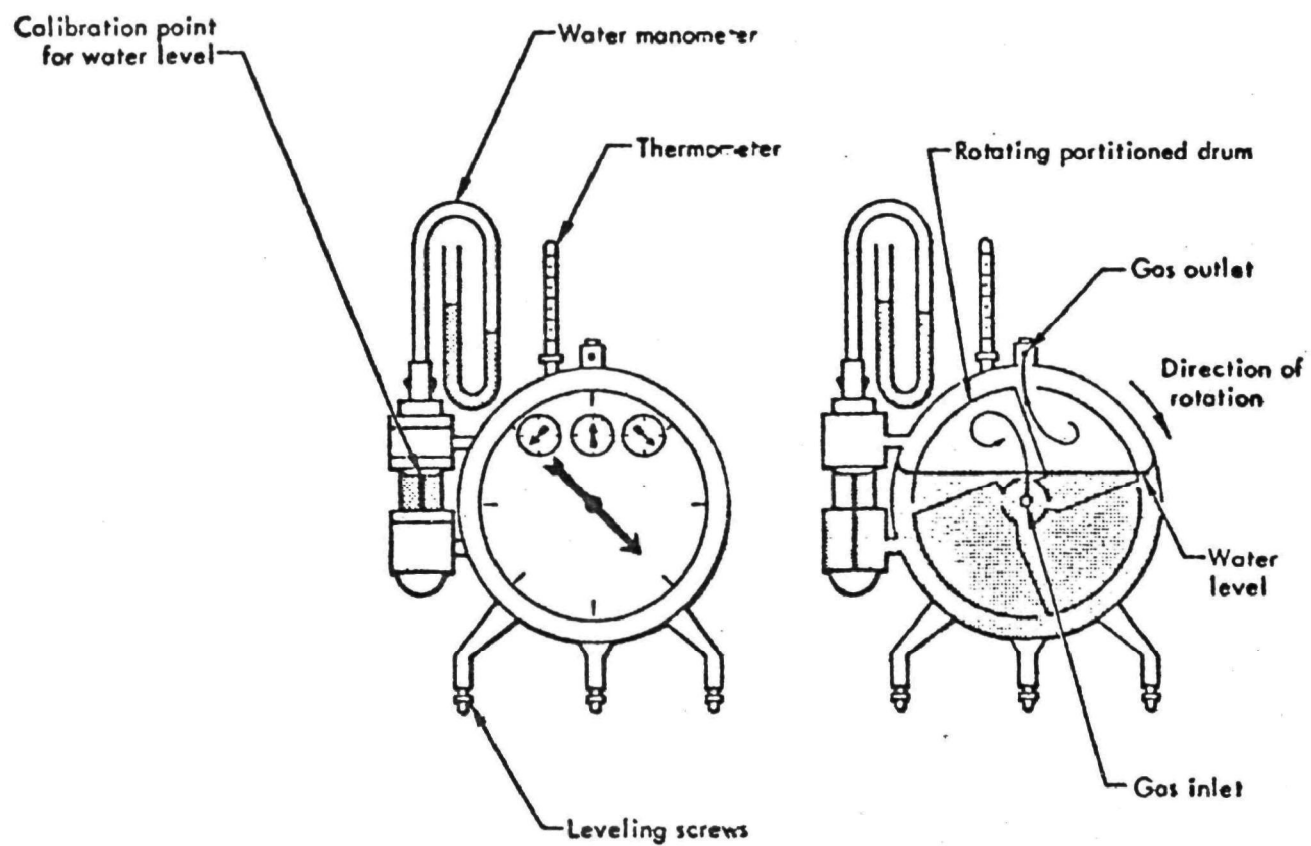


Figure 10.
Front and Cross-sectional View of a Wet Test Meter

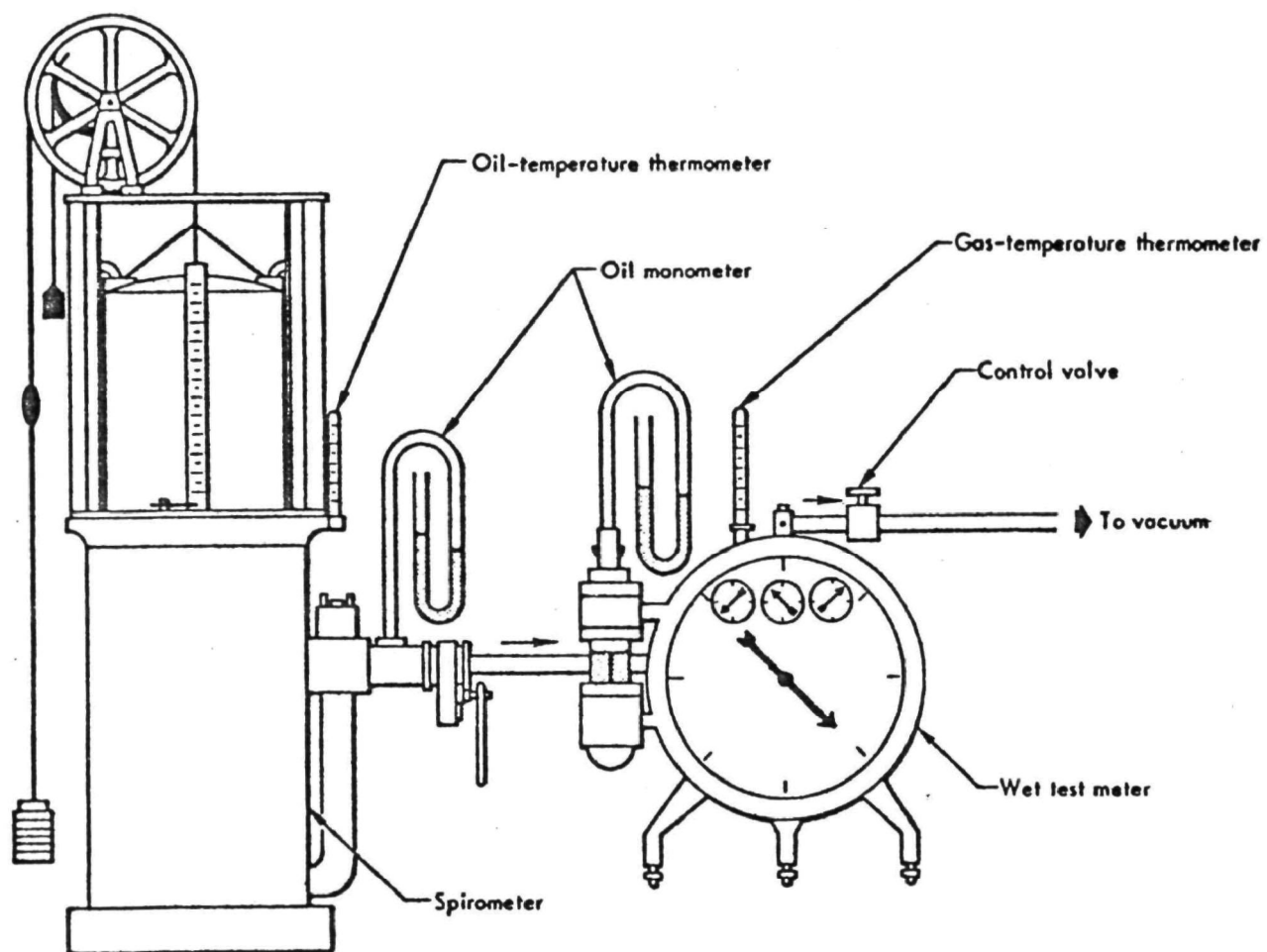


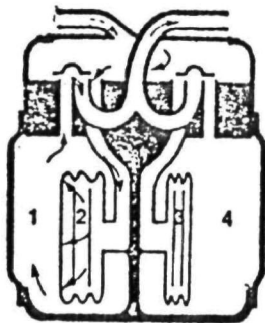
Figure 11.
Calibrating a Wet Test Meter with a Spirometer

$$V_{g \text{ std}} = V_g \frac{T_{\text{std}}}{T_a} \frac{P_a}{P_{\text{std}}} \quad [31]$$

- V_g = Volume of gas at room temperature and pressure (T_a , P_a)
 V_o = Volume observed from meter
 P_b = Barometric pressure during measurement
 T_a = Temperature of ambient air, °K
 H_m = Height of test meter manometer, inches H_2O
 P_w = Saturation water vapor pressure, mm Hg at T_a
 RH = Relative humidity at T_a (0 to 1.00)
 $V_{g \text{ std}}$ = Volume of gas at standard temperature and pressure
 $(T_{\text{std}}, P_{\text{std}})$
 1.87 = Conversion factor: inches H_2O to mm Hg pressure

Dry Test Meters

Dry test meters are very popular, both for use in the laboratory and in the field. Millions of them are used in industry, commerce, and residential homes for measuring natural and other gas volumes. They are versatile, come in many sizes, and can operate over wide ranges of temperature (-30 to 140°F), pressure (350 psig maximum) and flowrates (5 to 50,000 liters/min). They may be made from various types of materials including iron, aluminum, brass, copper, and plastics. Their basic structure consists of two bellows like chambers inside two larger compartments giving a total of four chambers [Figure 12]. The chambers fill and empty sequentially. Gas flow direction is controlled by two "D-slide" (because of their shape) valves. As the gas enters one of the bellows-like chambers, it expands pushing gas out of the outer chamber [Figure 12]. Through proper linkage and timing the gas flow is shifted to the second bellows chamber when the first is filled, repeating the process. The third sequential step has the gas entering into the first outer chamber, pushing gas out of the inner flexible chamber. The



Chamber 1 is emptying,
2 is filling, 3 is empty,
and 4 has just filled.



Chamber 1 is now empty,
2 is full, 3 is filling,
and 4 is emptying.



Chamber 1 is filling,
2 is emptying, 3 has
filled, and 4 has
emptied.



Chamber 1 is now completely
filled, 2 is empty, 3 is
emptying, and 4 is filling.

From Crabtree

Figure 12.
How a Dry Test Meter Works

expanding and contracting motion of the bellows operate the slides and the calibrated dials. The diaphragms are generally made of long-lasting flexible synthetic materials. A differential pressure in the order of 0.5 inch H_2O results from operational and friction losses. Unless excessively corrosive gases are used, dry test meters last up to thirty years with proper maintenance.

Dry test meters can be calibrated in the same manner as wet test meters. The usual accuracies are of the order $\pm 1\%$. If larger variations are found, they may be corrected by adjusting tangential weights which affect the volume-dial linkage.

Rotary Displacement Meters

A popular positive displacement meter is the two-lobe or "Figure 8" meter. A commercial unit in common use is known as a Roots meter. This type of meter consists of two contra-rotating lobes within a close-fitting housing [Figure 13]. The rotating lobes act as impellers which measure and dispense the gas with only a slight pressure drop of approximately 0.5 to 2.5 inches of water. The lobe contours are mathematically developed and accurately manufactured to form a continuous seal with each other without actual contact during rotation. The tips of the lobes form a like seal with the semicircular portions of the meter housing. As each lobe reaches a vertical position [Figure 13; Position 2], it traps a known volume of gas and displaces it to the outlet. In one complete revolution four similar gas parcels will be measured and passed to the outlet. The total volume of the four parcels is called the displacement volume per revolution of the meter. This displacement volume is permanent and non-adjustable. It is established by the machined contours of the non-wearing rotating parts and the non-wearing fixed parts. The displacement volume of the meter may be determined either by using a known volume of gas at a given temperature

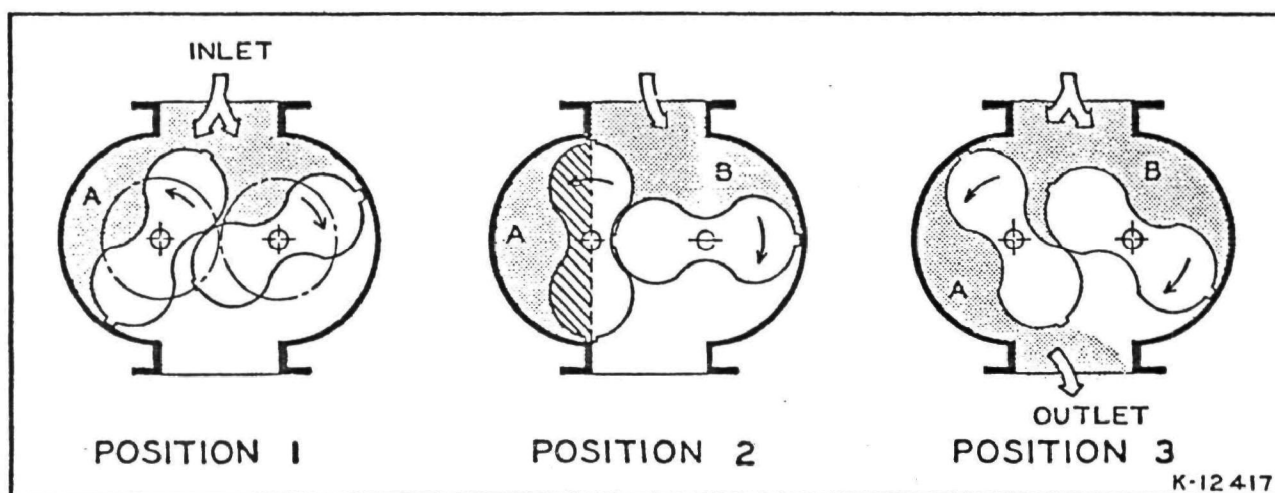


Figure 13.

Principle of Gas Flow Through a Roots Meter

and pressure, or by mathematical calculation from the known manufacturer's dimensions.

The meter is suitable for most non-corrosive, clean gases at either constant or widely varying flowrates. Various sizes of meters are available for flowrates varying from 0.5 to 3,000 liters per minute with accuracies of $\pm 1\%$. Maximum flowrates and pressures are specified by the manufacturer for a specific flowmeter and should not be exceeded. The meters can operate over a temperature range of -40° to 140°F depending on the manufacturers specifications. The meter is not suitable for liquids, corrosive gases, or gases that contain liquid or solid particulate matter that would tend to jam the moving parts.

Total volume of the gas passing through the meter is indicated by appropriate gearing and dials. Flowrates are obtained by dividing the indicated volume by the elapsed time. Some models have a timing mechanism which will give the flowrate directly. Gas volume corrections are made just as they are for the dry test meter. The observed meter volume (V_m) may be corrected for the pressure drop through the meter (ΔP_m) as follows:

$$V_g = V_m \frac{P_b - \Delta P_m}{P_b} \quad [32]$$

V_g = Volume of gas being measured

V_m = Volume indicated by meter

P_b = Barometric pressure, mm Hg

ΔP_m = Pressure drop through meter, mm Hg

Whenever it is desired to convert the measured volume (V_g) to the volume at a standard temperature (25°C ; 298°K) and pressure (760 mm), then:

$$V_{g \text{ std}} = \frac{P_a}{P_{\text{std}}} \cdot \frac{T_{\text{std}}}{T_a} V_g = 0.392 \frac{P_a}{T_a} V_g \quad [33]$$

where P_a and T_a are the meter, or actual, temperature and pressure of V_g .

SECONDARY STANDARDS

Secondary standard gas-flow measurement devices are generally calibrated with a primary or intermediate standard. They are extensively used in the field as well as the laboratory. Very often they form an integral part of instruments used for sampling and analyzing industrial process and waste gases as well as the ambient air. These devices include flowrate meters such as rotameters, orifice meters, and critical orifices, mass flowmeters, such as thermistors and thermocouples, and mechanical flowmeters, such as anemometers, velometers and magni-heliguages.

Rotameters

Rotameters are an extensively used form of variable area rate-of-flow meters. They are used for both gas and liquid volume flow measurements. They generally consist of a vertical transparent glass or plastic tapered tube containing one or two floats of differing densities [Figures 14, 15]. Tube sizes vary from one-sixteenth inch for low flowrates to as much as twelve inches for high flowrates. The velocity of the fluid (gas or liquid) moving up the tube decreases due to the increasing annular space between the tapering walls and the float. The floats rise until the gravitational forces equal the combined buoyant and drag forces of the moving fluid. The height of the float at its equilibrium position is a

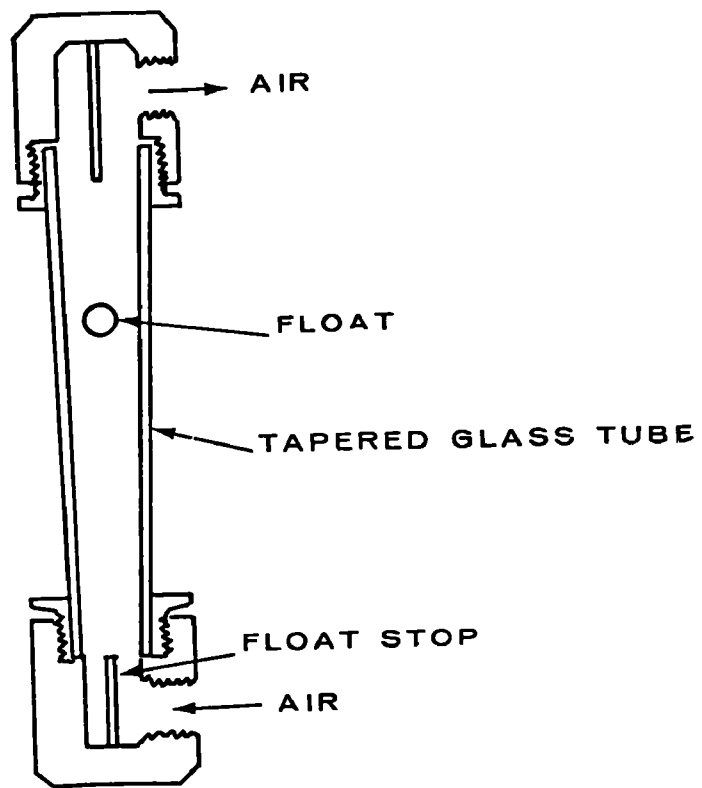


Figure 14.
Cross-sectional View of a Variable Area Rotameter

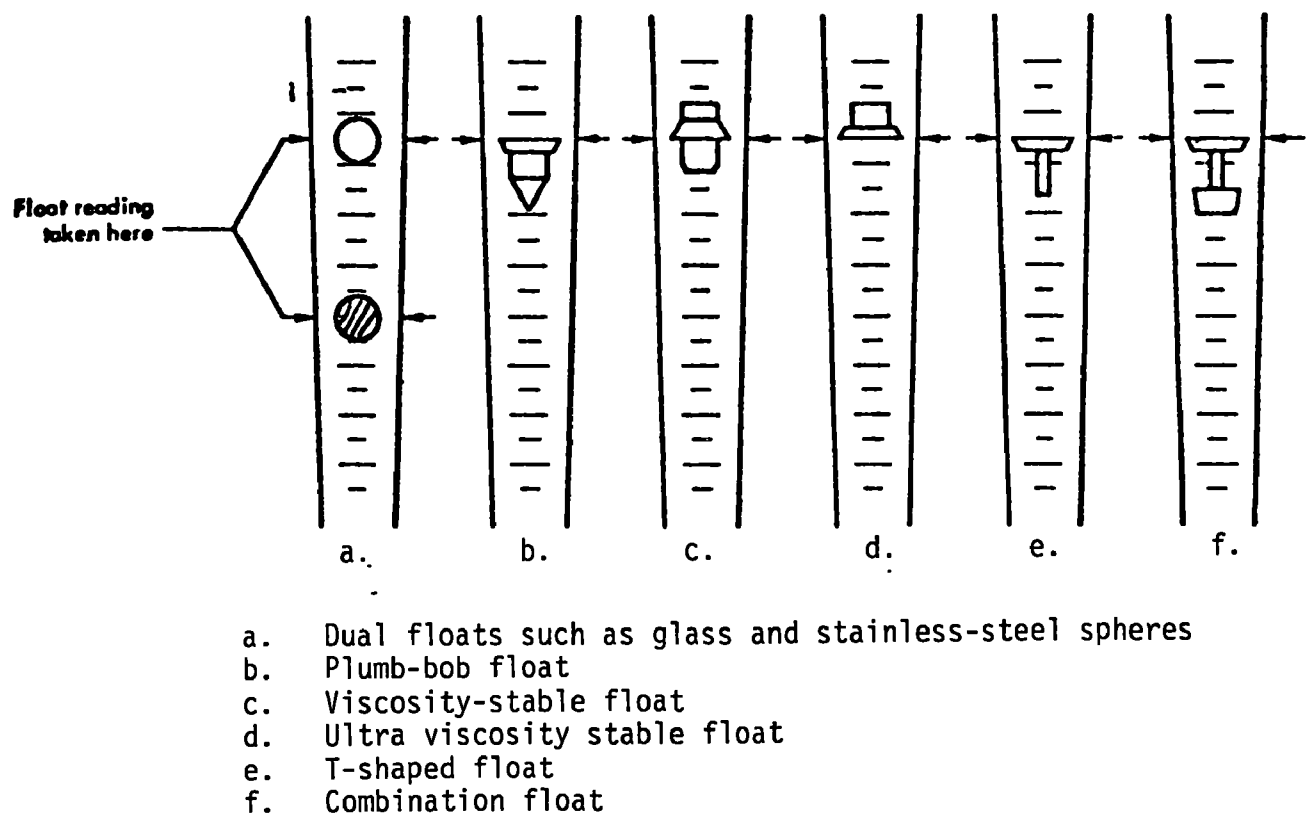


Figure 15.

Various Types of Rotameter Floats

measure of the flowrate which is read either directly from a scale on the tube or from a calibration curve. The height is always taken at the widest dimension of the float [Figure 15].

The scale may be linear, non-linear, or logarithmic depending on the flowrate range covered and the taper of the tube. Mechanical, magnetic, or electrical float height indicators are used for fluids that are not transparent or when metal tubes are used. The floats may be made of glass, ceramics, or metals of various densities. A combination of a glass and stainless steel float in the same tube is often used. The second float with the greater density conveniently extends the range of the flowmeter.

The flowmeter range of a single rotameter tube covers approximately 10 to 100 times the smallest flow unit (i.e. 1-10 or 1-100 ml/min., cfm etc.). The range of a rotameter can be extended by the use of supplementary tubes having a wider or narrower bore. A full set of rotameters can measure gas flowrates from 1 ml/min to 9 m³/min. Rotameters have been used at pressures up to 300 psig and temperatures of -50 to 400°F. They can be accurate to 1 to 2% if carefully manufactured and calibrated, but are often used to give rapid, visual indication of the flowrate. They suffer from float oscillation with pulsing, or rapidly changing flowrates. Surge bottles generally will correct such oscillations if placed upstream of the rotameter for pressurized sources and downstream for vacuum induced flow. Vapors in the gas may condense and contaminate the rotameter if they are near their dew points.

Calibration of rotameters for gas flowrates may be accomplished by the use of any of the standard or intermediate standard devices. In general, it is best to calibrate the rotameter with the gases and under the conditions of use. Figure 16 schematically shows how a rotameter is calibrated for measuring the air flowrate passing through a midget

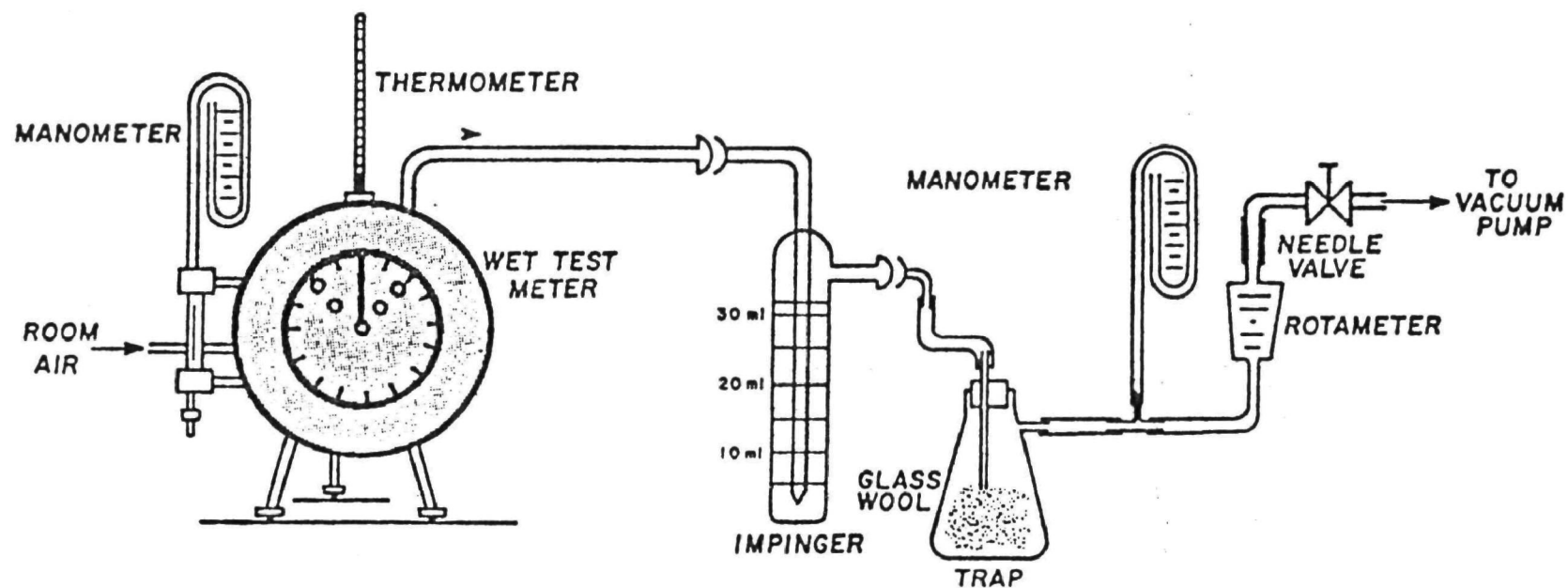


Figure 16.

Calibration of a Rotameter with a Wet Test Meter
 (Note that other measuring or sampling methods may be calibrated in this manner)

impinger. Note that the wet test meter is placed at the front of the sampling train so that the volume of entering air is measured directly. A glass wool trap is placed after the impinger to catch any mist or spray which might coat the rotameter ball and tube and give erroneous results due to increased weight, smaller annular space or friction with the sides. The glass wool is loosely packed to prevent unnecessary and possibly interfering pressure drops. The advantage of the system shown in Figure 6 is that the effect of the pressure drop through the impinger is automatically included in the calibration curve. Any other sampling device (fritted bubbler, filter head, etc.) may be substituted for the impinger. Conversely, any other flow measuring device (fixed or critical orifice, hot wire anemometer, etc.) may be calibrated in the place of the rotameter. In addition, the wet test meter can be replaced with any primary or secondary calibration device.

The calibration curve for the rotameter will hold in the field within $\pm 4\%$ if the temperature and pressure do not vary from the calibration temperature and pressure by no more than $\pm 10^\circ\text{C}$ (18°F) and ± 30 mm Hg pressure. If there is a greater difference, or if greater accuracy is possible and desired, the following approximate correction may be applied:

$$Q_a = Q_c \sqrt{\frac{P_c}{P_a} \cdot \frac{T_a}{T_c}} \quad [34]$$

Q_a = Actual flowrate during sampling

Q_c = Observed flowrate obtained from calibration curve prepared in the laboratory

P_c = Pressure of calibration air, mm Hg

T_c = Temperature of calibration air, $^\circ\text{K}$ or $^\circ\text{R}$

P_a = Pressure of air in field, mm Hg

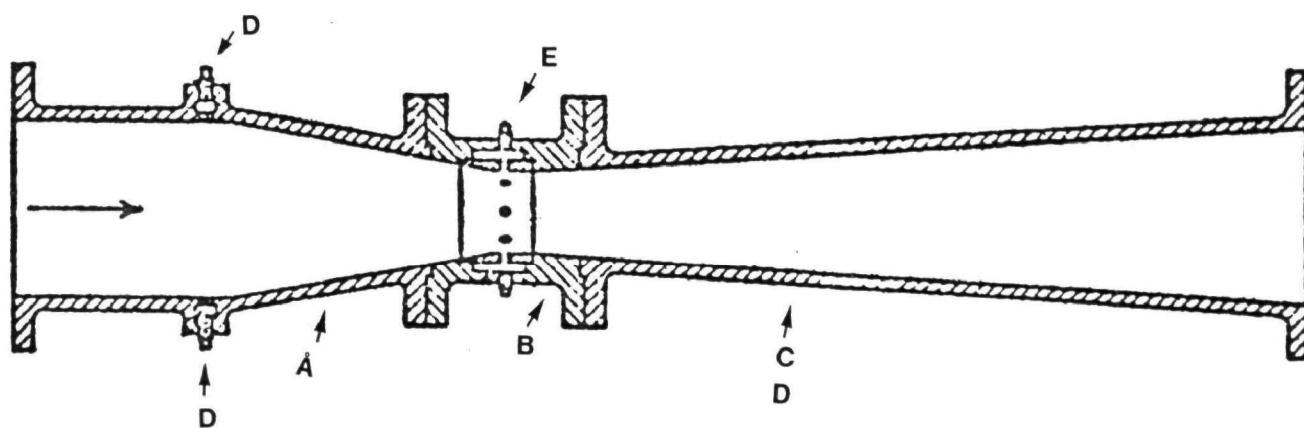
T_a = Temperature of air in field, $^\circ\text{K}$ or $^\circ\text{R}$

Orifice Meters

Orifice meters have been used extensively in industry for many years. They furnish a convenient and accurate method for measuring fluid (gas or liquid) flow in a pipe. They operate on the principle that as a fluid passes through a constriction in the diameter of a pipe the velocity of the fluid increases while its pressure drops [Figures 17, 18]. A measure of the pressure drop gives a measure of the flowrate of the fluid. The pressure drop depends on the type and amount of constriction but generally is one to two orders of magnitude greater than the differential pressure measured by a pitot tube. If the physical properties of the fluid and the dimensions of the pipe and its constriction are known, the theoretical flowrate can be calculated. In practice, however, the flowrate is never equal to the theoretical rate and an overall coefficient of discharge (α) for each type of orifice must be determined.

There are three general types of orifice meters: venturi, nozzle, and plate. The first two are similar; they require more careful design and installation and cannot be easily varied to cover a wider range of flowrates and fluid types. However, if properly designed, abrupt flow disturbances are avoided, energy loss is minimized, and the coefficient of discharge is usually near unity making mathematical calculation of the flowrate possible.

Thin Plate Orifice Meters. The plate orifice is more popular for measuring wider ranges of flowrates and fluid composition. The orifice plates are relatively easy to manufacture, install and change, and the orifice requires less pipe length and space [Figure 18]. Equation 35 indicates the factors involved in the calculation of the flowrate through the orifice.



- A. Inlet section
- B. Throat section
- C. Outlet section
- D. Upstream Pressure tap
- E. Downstream pressure tap

Figure 17.
Venturi Meter

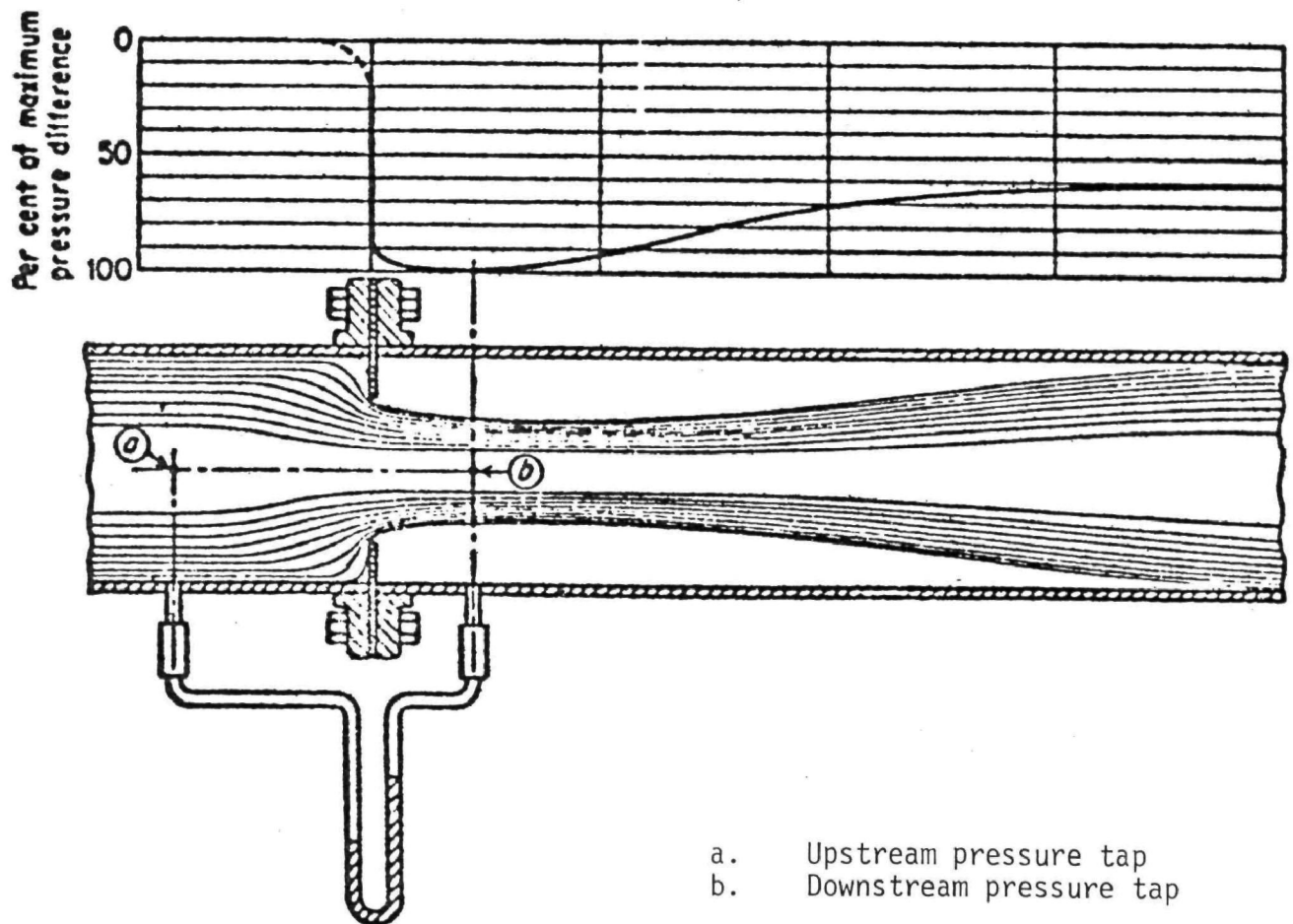


Figure 18.
Thin Plate Orifice Meter

$$Q_w = \alpha A_o G \sqrt{\frac{2\rho_1(P_1 - P_2)}{1 - m^2}} \cdot \sqrt{\frac{(1 - m^2) \frac{\gamma}{\gamma - 1} \frac{1}{1 - \phi} \left(1 - \phi \frac{\gamma - 1}{\gamma}\right) \phi^{2/\gamma}}{1 - m^2 \phi^{2/\gamma}}} \quad [35]$$

- Q_w = Weight rate of flow
 α = Coefficient of discharge of the orifice (usually determined experimentally)
 A_o = Area of the orifice opening
 G = Force of gravity
 ρ_1 = Density of gas upstream of orifice
 P_1 = Upstream gas pressure
 P_2 = Downstream gas pressure
 m = Ratio of pipe diameter to orifice diameter
 γ = Ratio of specific heat at constant pressure to that at constant volume, C_p/C_v
 ϕ = Ratio of downstream pressure to upstream pressure

The second square root term of equation 35 adjusts the equation for the compressibility of the flowing fluid. It can be replaced by a single term, E , the compressibility factor, to render a general equation:

$$Q_w = E \alpha A_o G \sqrt{\frac{2\rho_1(P_1 - P_2)}{1 - m^2}} \quad [36]$$

For incompressible fluids or for gases near normal atmospheric pressures, the compressibility factor, E , is essentially one and may be ignored.

Orifice meters may be calibrated experimentally with any of the primary or intermediate standards. The flowrates for a given orifice meter are within limits proportional to the square root of the pressure drop. A plot of the flowrate versus the square root of the pressure drop should give a straight line for flowrate ranges covering pressure drops of several inches of water. A plot of flowrate versus pressure drop would give a usable but curved line.

For atmospheric measurements, a laboratory calibration curve would hold within $\pm 4\%$ for atmospheric pressure changes of ± 30 mm Hg and temperature changes of $\pm 10^\circ\text{C}$ (18°F). For greater changes or for a more accurate approximation, the flowrate may be calculated from equation 36. However, by assuming that only the density of the air (ρ_1) in equation 36 changes and that all other parameters remain essentially constant, an approximate correction may be obtained by equation 34.

When sampling power plant stacks or other types of gases, the molecular weight of the gas can differ from the "molecular weight" of air. If the orifice has been calibrated with air then an additional term should be introduced into equation 34 to compensate for the effect of the molecular weight (or gas composition) change on the gas density, i.e.:

$$Q_a = Q_c \sqrt{\frac{P_c}{P_a} \cdot \frac{T_a}{T_c} \cdot \frac{MW_c}{MW_a}} \quad [37]$$

- Q_a = Sampling flowrate in field
- Q_c = Flowrate obtained from calibration chart
- P_c = Pressure of calibration air, mm Hg
- P_a = Pressure in field, mm Hg
- T_c = Temperature of calibration air, $^\circ\text{K}$ or $^\circ\text{R}$
- T_a = Temperature in field, $^\circ\text{K}$ or $^\circ\text{R}$
- MW_c = "Molecular Weight" of calibration air (Equation 9)
- MW_a = "Molecular Weight" of gas being measured (Equation 9)

Capillary Orifice Meters. In many laboratories, orifice meters are constructed from small bore glass tubing combined with a U-tube manometer [Figure 19]. For gas velocities up to near the speed of sound, the flowrate is a function of the pressure drop and the length

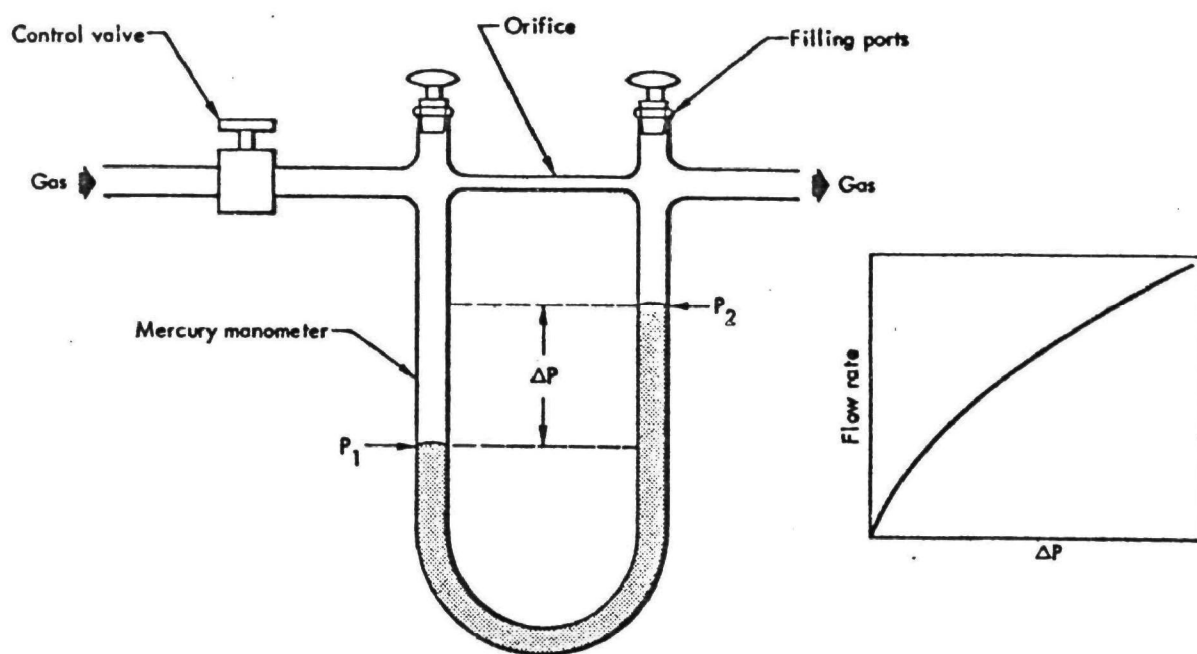


Figure 19.
Typical Capillary Orifice Meter and Calibration Curve

of the tubing (or capillary). This type of orifice meter may be calibrated directly by any of the primary or intermediate methods described above. The flowrate may also be calculated by the following equation if the kinetic effects at the beginning and ending of the tube or capillary can be neglected.

$$Q = \frac{\pi(P_1 - P_2) \left(1 + \frac{P_1 - P_2}{2P_2}\right) r^4}{8\mu L} \quad [38]$$

- Q = Volumetric gas flowrate
- P_1 = Upstream gas pressure
- P_2 = Downstream gas pressure
- r = Internal capillary radius
- μ = Viscosity of gas
- L = Length of capillary tube

Table 5 gives viscosity data for a number of common gases, and Table 6 shows the variation of the viscosity of air with temperature. Except for low and very high pressures, the viscosity of air is relatively independent of the pressure.

Critical Orifices. Critical orifices are popular for use in situations where a constant air flowrate is desired. They are easily constructed from hypodermic needles, capillary tubing, and polyethylene or Teflon rods. They are also easily calibrated with any of the primary or intermediate standards as described above [Figure 20].

Table 5
GAS-VISCOSITY DATA^a

Gas	Temperature (°C)	Viscosity (micropoises)
Air	18	182.7
Carbon dioxide	20	148.0
Carbon monoxide	21.7	175.3
Chlorine	20	132.7
Ethane	17.2	90.1
Ethylene	20	100.8
Helium	20	194.1
Hydrogen	20.7	87.6
Hydrogen chloride	18	142.6
Hydrogen sulfide	17	124.1
Methane	20	198.7
Nitric oxide	20	187.6
Nitrogen	27.4	178.1
Nitrous oxide	26.9	148.8
Oxygen	19.1	201.8
Propane	17.9	79.5
Sulfur dioxide	20.5	125.4
Xenon	20	226.0

a From Chemical Rubber Co. Handbook

Table 6
VARIATION OF VISCOSITY OF AIR WITH TEMPERATURE^a

Temperature °C	Viscosity (Micropoises)
-194	55
-104	113
0	171
18	183
40	190
74	210

a From Chemical Rubber Co. Handbook

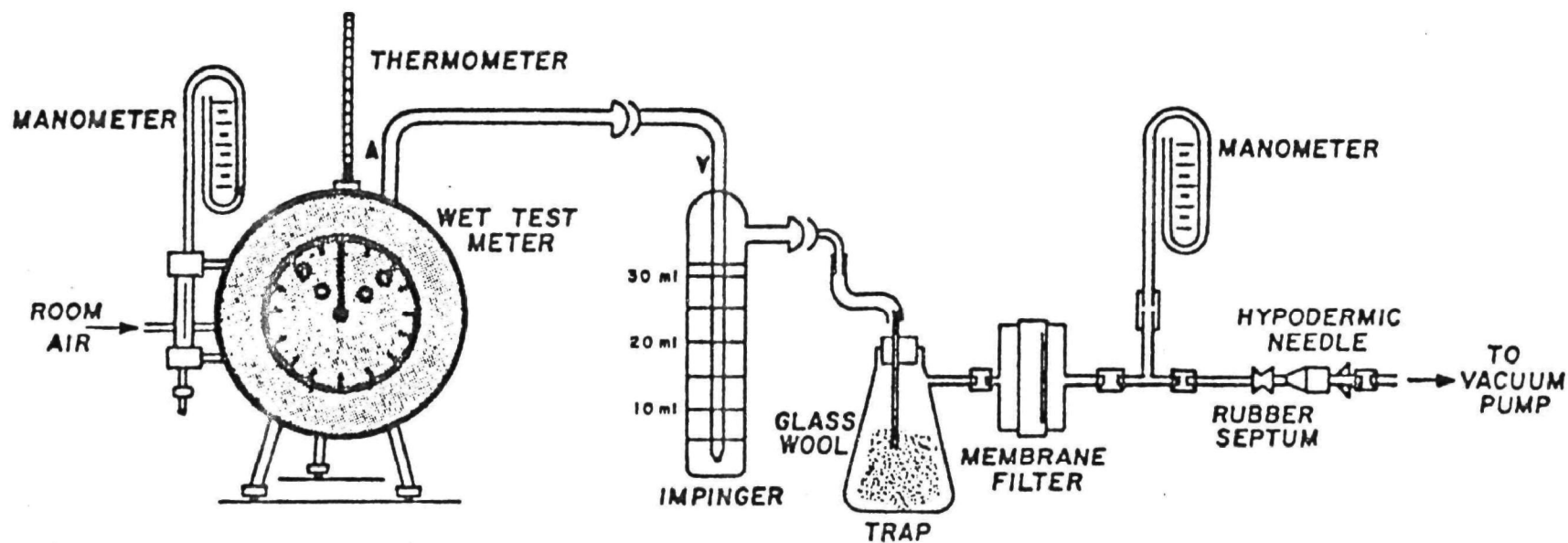


Figure 20.
Calibration of a Critical Orifice with a Wet Test Meter

The air flowrate through the orifice becomes critical when its velocity is equal to that of sound. This occurs when the downstream pressure is reduced to 53% or less of the upstream pressure. The air velocity becomes constant and independent of any excess vacuum on the downstream side. Thus a constant and known flowrate can be maintained by merely taking the precaution to keep a vacuum of 53% or more of the upstream pressure [Figure 21] on the downstream side of the critical orifice.

The theoretical treatment of the flowrate is quite complex. The following relationship has been derived for a perfect gas:

$$Q_{\max} = \alpha A_2 P_1 \left[\frac{G \gamma \text{MW}}{RT} \left(\frac{2}{\gamma+1} \right)^{(\gamma+1)/(\gamma-1)} \right]^{\frac{1}{2}} \quad [39]$$

- Q_{\max} = Maximum flowrate, mass per unit time
- α = Discharge coefficient of critical orifice
- A_2 = Cross-sectional area of critical orifice
- P_1 = Upstream gas pressure
- G = Gravity force constant
- γ = Ratio of specific heats C_p/C_v
- MW = Molecular weight of gas
- R = Gas constant
- T = Gas temperature, absolute

Equation 39 shows the various factors that affect the maximum flowrate of a critical orifice. They include a discharge coefficient, α , which is an empirical factor to account for physical aberrations in the orifice. It can change with slight changes in the surface or diameter of a critical orifice and with changes in the Reynolds number of the flowing gas stream. The molecular weight of the gas, its temperature and pressure, and the specific heat ratio (i.e. C_p/C_v) are also

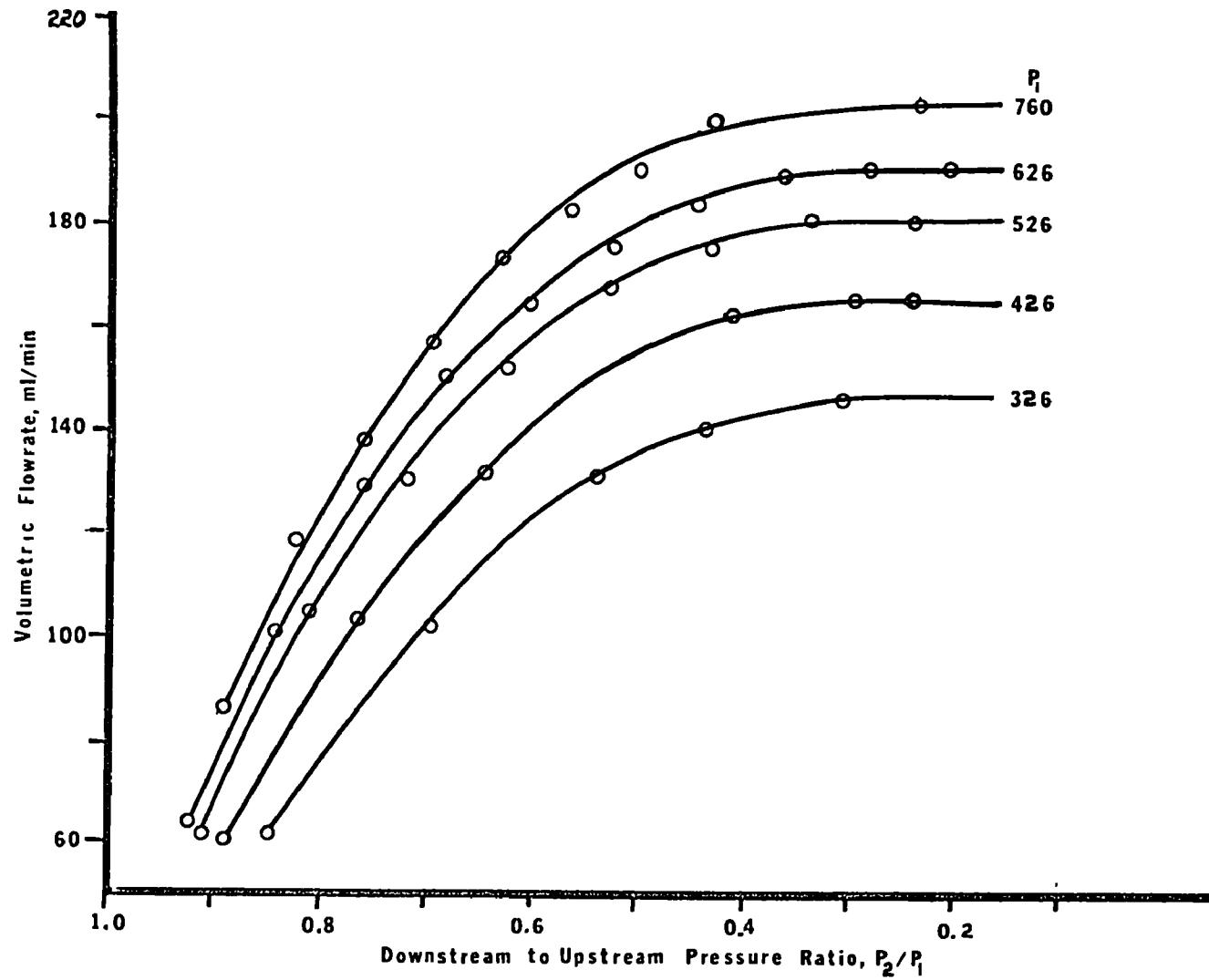


Figure 21.
Variation of Volumetric Flowrate Through a No. 27 Gauge Hypodermic Needle as a Function of Downstream (P_2) to Upstream (P_1) Pressure Ratios

of importance. Any changes of any of the above factors would affect the flowrate as indicated by equation 39.

For air, many of the variables of equation 39 are known or can be estimated (K), and the following simplified equation may be used.

$$Q_{\max} = K \cdot \alpha \cdot \frac{A_2 P_1}{\sqrt{T}} \quad [40]$$

In this case, Q_{\max} is a direct function of the physical structure (K, α , and A_2) of the critical orifice as well as the upstream pressure, P_1 . The flow is also inversely proportional to the square root of the absolute temperature. From equation 40 it follows that for a given critical orifice calibrated in a laboratory and then used in the field, the following equation may be used for obtaining the critical flowrate in the field from the critical flowrate obtained in the laboratory.

$$Q_{\max-a} = Q_{\max-c} \frac{P_a}{P_c} \sqrt{\frac{T_c}{T_a}} \quad [41]$$

where "a" and "c" indicate the field (or actual) and calibration values, respectively. If the sampling device (filter, impinger, or other) is placed before the critical orifice, P_a (or P_1) is equal to the barometric pressure minus the pressure drop caused by the sampling device.

In practice, a difference of $\pm 25^\circ\text{C}$ (45°F) in temperature causes an error in the order of $\pm 4\%$. A pressure variation of ± 25 mm Hg (1 inch Hg or 13.6 in H_2O) would also cause an error of approximately $\pm 4\%$. The errors would be additive if the pressure and temperature changes were in the same direction. They would offset each other if the changes were in the opposite direction, i.e. if one increased while the other decreased.

Table 7 shows the range of flowrates that can be obtained with hypodermic needle critical orifices varying in size from gauge number 13 through 25 and in length from 1/2 to 3-1/2 inches. It also shows that manufacturing uniformity for a given batch of needles gives flowrates reproducible to a relative standard deviation of less than 10% and more usually less than 5% for the larger gauge and longer length needles. The flowrate decreases slightly with the number of times the needles are used. A small percentage of needles plug on first use, and the percentage of plugging increases with reuse. To prevent serious plugging, the orifice needs the protection of a membrane, or equivalent, filter between it and the sampling device [Figure 20]. Since calibration is rapid once the apparatus has been set up, it is suggested that the needles be calibrated frequently. In cases where greater accuracy is desired, the calibration should be conducted before and after each use.

HEAT TRANSFER ANEMOMETERS

The movement of air can be measured by its ability to absorb heat from a heated probe. The probe may be in the form of a wire, thin metal film, thermistor, or thermocouple. Equation 42 below, gives the theoretical relationship for the rate of heat loss from a wire maintained at a fixed temperature above that of the flowing gas.

$$H = k\theta + (2\pi k C_v \rho d v)^{\frac{1}{2}} \theta \quad [42]$$

- H = Rate of heat loss per unit length of wire
- k = Thermal conductivity of gas
- θ = Number of degrees above temperature of gas
- C_v = Specific heat at constant volume of gas
- ρ = Density of gas
- d = Diameter of wire
- v = Velocity of gas

Table 7

Flowrate (liters/min) as a
Function of Needle Gauge and Length

(Measured at 630 mm Hg. Each flow rate is the mean for 12
Becton-Dickenson (B/D) needles. Values in () are the
percent relative standard deviations of flow rates.

Gauge	Needle Length, in.									
	3 1/2	3	2 1/2	2	1 1/2	1 1/4	1	3/4	5/8	1/2
13	12 2(2)									
15	8 9(1)									
17				5.89(1)						
18				3 77(3)	4 1 (3)		4.45(2)			
19		2.15(7)		2 37(5)	2.43(5)	2.58(3)				
20			1.67(5)	1 75(1)	1.83(3)	1 97(1)	1 97(2)			
21				1.23(2)	1.32(3)	1.38(2)	1.47(3)			
22		.59(15)		.68(4)	.80(3)	.76(6)	.89(3)			
23				.42(2)	.49(4)	.54(2)	.54(6)	.69(6)	.61(5)	.63(5)
24					.29(3)	.40(3)	.42(5)	.45(4)	.50(5)	.51(4)
25				.19(5)			.26(4)	.31(3)	.31(6)	.34(9)

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As can be seen from equation 42 a number of factors affect the rate of heat loss (H) by a given probe. In addition to the temperature and diameter of the wire, the thermal conductivity, specific heat, and density of the moving gas as well as its velocity are of importance in removing heat. Changes in any of these factors would change to a proportionate degree the output of the sensor.

In practice, two probes are used [Figure 22]. One does the actual sensing while the second is partially or entirely shielded from the gas flow and is used as a reference for the first. The electronic circuitry of the unit controls the current to the sensors and maintains a fixed voltage and/or current across the two probes. The output generally is a DC voltage proportional to the heat loss which in turn is proportional to the mass flowrate of the gas.

The advantages of heat transfer anemometers is that the output is in actual mass flow units directly convertible to standard temperature and pressure gas flowrates. The output is not linear but can be with proper electronic circuitry. Accuracies of $\pm 0.5\%$ with repeatabilities of $\pm 0.1\%$ are common. For well-designed and calibrated units accuracies of $\pm 2\%$ are obtainable with changes of as much as $\pm 30^\circ\text{C}$ ($\pm 54^\circ\text{F}$) in temperature and 1/3 to 3 atmospheres in pressure.

There are some disadvantages. The heated wires or probes can react with corrosive, flammable, or reactive gases causing possible calibration changes or explosive situations. Particulate or foreign matter can also collect on the probes and give erratic results. Some units have self-cleaning circuits to prevent such contamination. The resistance-temperature coefficient of a thermistor is inverse to but much greater than that of a heated wire; however, at lower temperatures the coefficient changes rapidly and non-linearly at very low pressures. In general, the cost of heat transfer units is relatively high. The electronic circuitry necessary for ease of calibration, linearized output, output stability, etc. is relatively difficult to manufacture.

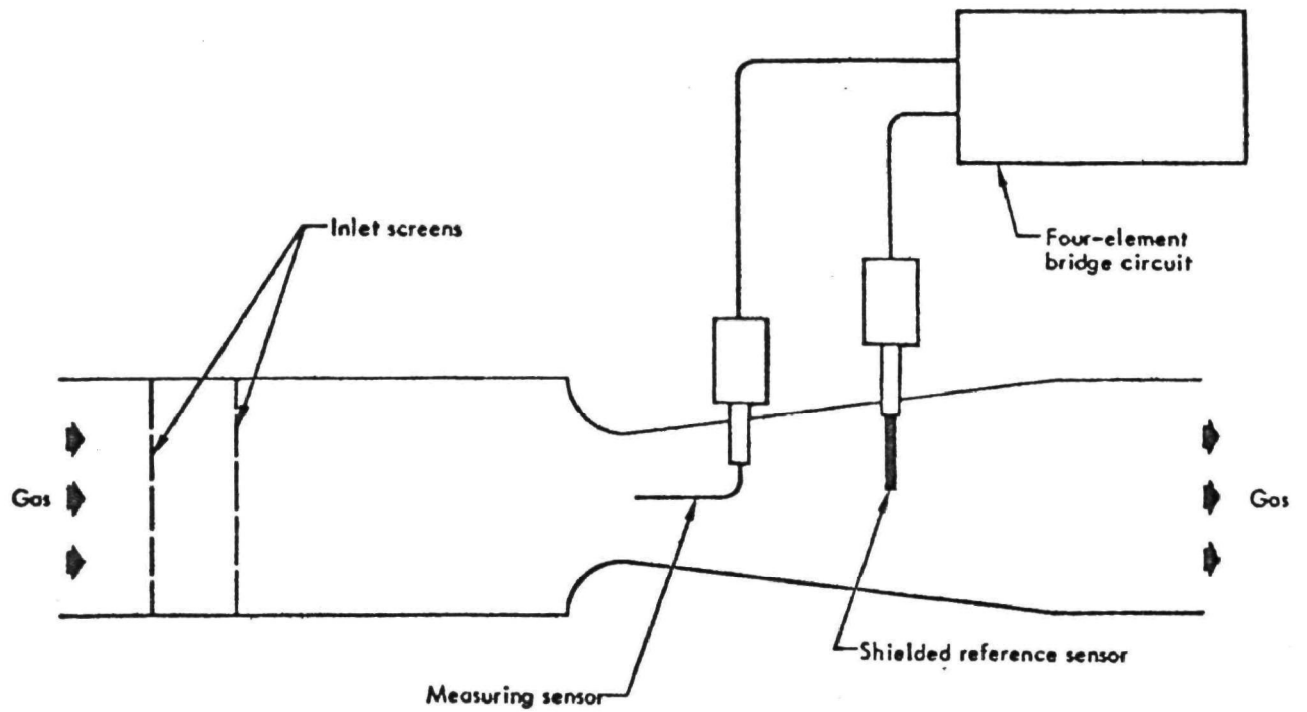


Figure 22.

Cross-section of a Temperature-compensated Gas Flow Anemometer

BIBLIOGRAPHY

- Ower, E., and Pankhurst, R.C. "The Measurement of Air Flow," Pergamon Press, 1966.
- Nelson, G.O. "Controlled Test Atmospheres," Ann Arbor Science, Ann Arbor, Michigan, 1971.
- "Fluid Meters: Their Theory and Application," Sixth Edition, ASME Research Committee on Fluid Meters, H.S. Bean, Ed., American Society of Mechanical Engineers, New York, 1971.
- "Atmospheric Sampling," Institute for Air Pollution Training, Environmental Protection Agency, Research Triangle Park, N.C. 1972.
- Brenchley, D.L., Turley, C.D., and Yarmac, R.F. "Industrial Source Sampling," Ann Arbor Science, Ann Arbor, Michigan, 1973.
- Perry, R.H. and Chilton, C.H. "Chemical Engineers' Handbook," 5th Edition, McGraw Hill, New York, 1973.
- McCabe, W.L. and Smith, J.C. "Unit Operations of Chemical Engineering," Third Edition, McGraw Hill, New York, 1976.
- "Guide to Rotameter Application," Technical Bulletin No. T-022 Revision E, Brooks Instrument Division, Hatfield, Pa., 1977.

FIGURE CREDITS

The figures used in this document were taken wholly or in part from the following sources. Figures 6 - 9, 16 and 20 from various EPA documents; 2, 5, 10, 11, 19 and 22 from Nelson; 17 and 18 from McCabe and Smith; 12 and 13 from manufacturer's literature; and 1 from A. H. Strahler "The Earth Sciences," 2nd Ed, Harper and Row, 1971.